Chapter 8
The Age of Dinosaurs in the Land of Gonds

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Abstract The fossil record of dinosaurs from India provides a highly significant contribution to understanding the origin and evolution of dinosaurs and their paleobiogeographic significance. As India rifted from Gondwana and drifted northwards during the age of dinosaurs, the mobile episode in Indian geology provides a unique opportunity to study the diversity of dinosaurs in time and space. The dinosaurs from the Gondwana and post-Gondwana sediments of India have been collected and studied since their discovery in the 1920s, but the full range of their significance and evolutionary history remained fragmentary. After the independence of India, a renaissance arose in the study of dinosaurs at the Indian Statistical Institute (ISI) under the leadership of Pamela Robinson, as more and more dinosaur skeletons were discovered from different localities. This exploration by ISI paleontologists represented a pivotal moment in the history of vertebrate paleontology in India and became a starting point for a remarkable increase in our knowledge of Triassic, Jurassic, and Cretaceous dinosaur faunas. It inspired a new generation of students working under Ashok Sahni's direction at Panjab University to engage in the Cretaceous research. This paper offers an updated and comprehensive review of the anatomy, systematics, and evolution of Indian dinosaurs within historical, paleobiogeographic, and paleoecologic contexts. The occurrence of Indian dinosaurs is currently restricted to central and southern India, and the record extends across all three Mesozoic periods. It is generally regarded that dinosaurs originated in the Late Triassic Period in Argentina, about 230 million years ago. However, *Alwalkeria*, a theropod discovered in the Lower Maleri Formation of India, was contemporaneous with the oldest Argentinean dinosaurs. Similarly, *Barapasaurus* from the Early Jurassic Kota Formation is considered as one of the oldest, gigantic sauropod dinosaurs with a quadrupedal pose. The Late Triassic and Early Jurassic dinosaurs of India are diverse and document their early radiation. With the breakup of Gondwana, India began to disintegrate and drifted northwards, carrying its dinosaur fauna like a passenger ship, until it collided with the Oman-Kohistan-Ladakh Arc in the Late Cretaceous, forming a biotic corridor to Africa and Europe. The Late Cretaceous dinosaurs from the Lameta Formation, consisting of several species of titanosaurs and abelisaurs, provide intimate documentation of the last 'geologic minutes' before their extinction. Along with dinosaur bones, the largest titanosaurid hatchery is known from the Lameta Formation, extending for more than 1,000 km. Most egg clutches contain about 10 to 12 spherical eggs ranging in diameter from 15 to 20 cm. Surprisingly, these eggs were empty, showing no signs of embryos, perhaps indicating hatching failure during some environmental crisis. At the Cretaceous-Paleogene boundary, India was ground zero for two catastrophic events—the Shiva impact and Deccan volcanism—both linked to dinosaur extinction. The combination of twin asteroid impacts (Chicxulub and Shiva), with prolonged Deccan volcanism created an unprecedented and ultimately catastrophic environmental crisis across the globe, triggering the end-Cretaceous mass extinction.

Keywords Mesozoic • Sauropods • Abelisaurs • Cretaceous-Paleogene boundary • Shiva crater • India

Introduction

The dinosaurs were among the most successful animals ever to live on Earth, representing the glory of evolution and the mystery of extinction. For 166 million years, these reptiles ruled the Earth, flourishing in every continent from

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Antarctica to well beyond the Arctic Circle. To the astonishment and delight of most Indians, dinosaur bones and their nesting sites have been found in different regions of central and southern India. In recent times, India is gaining prominence as one of the important centers for dinosaur radiation. Although numerically and taxonomically less impressive than those of North America, China, Argentina, or Mongolia, the fossil record of India is highly important for understanding the origin and early evolution of certain clades of dinosaurs in Gondwana. There is a fascinating correlation between evolution of Indian dinosaurs and the continental drifting of the Indian plate from Antarctica to Asia over 160 million years. In the Early Cretaceous, as Gondwana began to break up, the Indian subcontinent began its northward journey across the equator carrying its precious dinosaur fauna and its nesting sites like a passenger ship during its collision course to Asia (Chatterjee et al. 2017). In this paper, I describe our current understanding on the origin, evolution, distribution, and paleobiogeography of Indian dinosaurs in three successive periods of the Mesozoic—Triassic, Jurassic, and Cretaceous—and their extinction event at the Cretaceous-Paleogene boundary. Along with the new dinosaur finds and their evolutionary significance, I here provide a historical narrative of the development of vertebrate paleontology in independent India.

Dinosaurs in Gondwana and Post-Gondwana Formations

India was the type area of the Gondwana formations, represented by the basal sequence of Late Paleozoic tillites, followed by fluvial sequences of shale, sandstone, and coal beds containing distinctive seed fern *Glossopteris* (Medlicott 1872). These unusual rocks were named 'Gondwana' meaning 'land of the Gonds,' because this area in central India is the home of the current Gond tribes, who had established a kingdom in the 14th century. The stratigraphic correlation of the Indian Gondwana formations with similar Gondwana rocks across Antarctica, Australia, South Africa, and South America gave birth to the concept of the supercontinent Gondwana and the continental drift theory (Wegener 1915). This ancient supercontinent Gondwana incorporated present-day South America, Africa, Arabia, Madagascar, India, Australia, and Antarctica. It was fully assembled by Neoproterozoic time, some 600 million years ago, and the first stage of its breakup began in the Early Jurassic Period, about 180 million years ago.

The Gondwana basins of peninsular India are traditionally considered extensional rift-basins in older Precambrian basement, which were reactivated in the Late Paleozoic through long-time subsidence, creating accommodation space for infilling Gondwana sediments. The basin-fill succession of Gondwana sediments, about 5-km-thick sequence, is characterized by a complex mosaic of fluvial-lacustrine deposits that range in age from Early Permian through Late Jurassic. The overlying Early Cretaceous Rajmahal/Jabalpur formations, and the Late Cretaceous Lameta/Kallamedu formations, and Deccan Trap are not included within the Gondwana Supergroup since by that time India had separated from Gondwana and was embarked on its northward journey (Chatterjee et al. 2017). The Gondwana basins occur along the extant river valleys and include four depocenters: (1) the Damodar, (2) the Son-Mahanadi, (3) the Satpura, and (4) the Pranhita-Godavari, of which the Pranhita-Godavari Valley strata contain a rich assemblage of early dinosaur fossils.

The fossil record of dinosaurs is biased toward lowland sedimentary environments especially the flood plain deposits. Unlike other parts of the world, the dinosaur faunas from Indian Gondwana and post-Gondwana sediments are limited in diversity through poor sampling and exploration, but are important from an evolutionary perspective. Indian dinosaur fossils hold the key to their early origin in the Late Triassic time, their acquisition of gigantic size in the Jurassic, their nesting behavior, dietary preference, in the Late Cretaceous during India's northward journey and finally their ultimate demise at the end of the Cretaceous.

There are eight successive horizons in the Gondwana and post-Gondwana sequences from which dinosaur faunas are currently known: (1) Upper Triassic (Late Carnian-Early Norian) Lower Maleri Formation); (2) Upper Triassic (Late Norian) Upper Maleri Formation; (3) Upper Triassic (Rhaetian) Lower Dharmaram Formation; (4) Lower Jurassic (Hettangian) Upper Dharmaram Formation; (5) Lower Jurassic (Sinemurian-Toarcian) Kota Formation; (6) Upper Jurassic (Tithonian) Bagra Formation; (7) Upper Cretaceous Nimar Formation (Cenomian-Turonian); and (8) Upper Cretaceous (Maastrichtian) Lameta and Kallamedu formations. Among these, the last two formations represent post-Gondwana sediments deposited following the break-up of Gondwana during the Cretaceous. These dinosaur-bearing horizons of India are shown in Table 8.1. It appears from the Table that India has a rapidly growing dinosaur record from Carnian to Maastrichtian with some major gaps in the Late Jurassic-Early Cretaceous interval (Chatterjee et al., 2017). Using an allegory of the four parts of the day, the Indian dinosaur dynasty is divided here into four episodes: dawn, day, evening, and night—chronologically narrating their origin, radiation, diversification, and finally their demise.

Table 8.1 Composite Gondwana and post-Gondwana formations of India (Dinosaur – bearing formations are shown by asterisk)

Age (Ma)		Era	Period	Epoch	Formation	Plate Tectonic and Global Event
66	POST-GONDWANA			Danian	DECCAN TRAP	END-CRETACEOUS EXTINCTION
		MESOZOIC	Cretaceous	Late	Lameta*/Kallamedu* Nimar*/Chikiala/Gangapur	OKL Arc Corridor Separation of Madagascar from India
				Early	RAJMAHAL TRAP	Separation of India from East Gondwana
145					Rajmahal/ Jabalpur	
	GONDWANA SUPERGROUP		Jurassic	Late	Bagra*	Gondwana Breakup
				Middle	Upper Kota*	
				Early	Lower Kota* Upper Dharmaram*	
201						END-TRIASSIC EXTINCTION
			Triassic	Late	Lower Dharmaram*	
					Maleri*/Tiki	
				Middle	Yerrapalli / Denwa	
				Early	Panchet / Kamthi	
252		PALEOZOIC	Permian			END-PERMIAN EXTINCTION
				Late	Kundaram	
					Raniganj	
				Middle	Barren Measures Barakar	Gondwana Coal Formation
				Early	Karharbari Talchir	Gondwana Deglaciation Gondwana Glaciation
300		PRECAMBRIAN				Gondwana Supercontinent
541						
3000			Precambrian		Precambrian basement	

Dawn: The Beginnings of Dinosaurs in the Late Triassic

The Triassic Period began soon after the most catastrophic event in geological history, at the end of the Permian, when life on Earth was almost (95% of species) completely wiped out during the end-Permian mass extinction by an environmental holocaust of a magnitude never seen before. In the aftermaths of the end-Permian extinction, some forms of life rebounded as death created opportunity, and survivors occupied vacant niches. Groups of animals that formerly played minor roles now assumed prominence, and new groups appeared.

The Late Triassic Period, ranged from 235 to 200 million years ago, was a pivotal time in vertebrate evolution - several major groups such as lissamphibians, turtles, lizards, crocodiles, dinosaurs, birds, mammals, and numerous extinct groups of archosauromorphs and archosaurs first appeared in the fossil record. When dinosaurs first originated in the terrestrial ecosystems in the Late Triassic, all the major continental plates were joined into a single supercontinent, Pangea, which slowly drifted northward (Wegener 1915) (Fig. 8.1). As Pangea rifted apart during the Late Jurassic and Cretaceous periods, a vast array of new body plans, structures, and levels of complexity evolved in the dinosaurs because of geographic isolation.

When dinosaurs first appeared in the fossil record during the Carnian stage of the Late Triassic as rare members of the archosaur communities, all the continents were still joined together in Pangea (Wegener 1915). One of the remarkable features of the Triassic was the widespread emergence of continents, followed by the extensive spread of nonmarine deposits, composed largely of redbeds. These redbeds were deposited in a complex river-floodplain-lacustrine system in many parts of the world and have yielded a rich record of the Triassic vertebrate fauna. In the Pangean world, dinosaurs and other tetrapods could migrate to any part of the globe over dry land, so continental Triassic vertebrates are quite similar across Pangea. However, there were both climatic

Fig. 8.1 Paleogeographic reconstruction of Gondwana during the Late Triassic (~220 Ma) (modified from Chatterjee and Scotese 1999)

and physical barriers that impede migration of some groups of tetrapods (Fig. 8.2). Climates were warm and uniform, since Pangea was symmetrically disposed above and below the equator, and dominated by monsoonal circulation in the coastal region. The heartlands of the Pangea were hot and dry. There were no ice caps in the polar regions.

Dense forests and swamps covered the land from the equator to high latitudes. The Triassic *Dicroidium* flora includes *Dicroidium*, spore-bearing true ferns, seed-bearing ferns, conifers, horsetails, cycads, and ginkgoes, which would have formed forests and swamps along the water's edge. The Triassic meadows and prairies of lowlands would have been covered in ferns, low cycads, club mosses, and horsetails. The uplands were dominated by coniferous forests. Inside these forests, a bewildering variety of small dinosaurs inhabited the dense understory. Other animals in the scene include several groups of archosaurs including crocodilians, pterosaurs, and birds, as well as frogs, turtles, lizards, and mammals.

In the Triassic Period, archosaurs replaced the therapsids as the dominant component of the terrestrial communities and became highly diversified. Archosaurs are divided into two primary lines, one leading to crocodilians (Crurotarsi), the other line to birds (Ornithodira) (Fig. 8.3A) (Chatterjee 1982a, 2015). The key character for the basal dichotomy of archosaurs seems to be different style of ankle joint. The Crurotarsi, which include phytosaurs, aetosaurs, rauisuchians, ornithischians, and crocodylomorphs, all have a crurotarsal joint. In this group, the astragalus and calcaneum articulate with each other by means of a peg-and-socket joint, allowing rotational movement between them.

The Ornithodira includes pterosaurs, lagosuchids, silesaurids, and dinosaurs (including birds). In this assemblage, the ankle joint is a mesotarsal hinge between the proximal and distal rows of the tarsal bones (Fig. 8.3D, E).

The Late Triassic is often called the 'Dawn of the Age of Dinosaurs,' even though dinosaurs were small and inconspicuous at that time and certainly not yet dominant. For millions of years they were but a small part of the reptilian fauna. These first dinosaurs were no larger than a terrier, with a long neck and a long and stiff tail. They had to compete for survival with larger contemporary reptiles, most notably the crocodile-like phytosaurs and fearsome rauisuchians. By the time early dinosaurs came on the scene, they had already evolved into three major lineages—sauropodomorphs, theropods, and ornithischians—with different dietary behaviors and modes of locomotion.

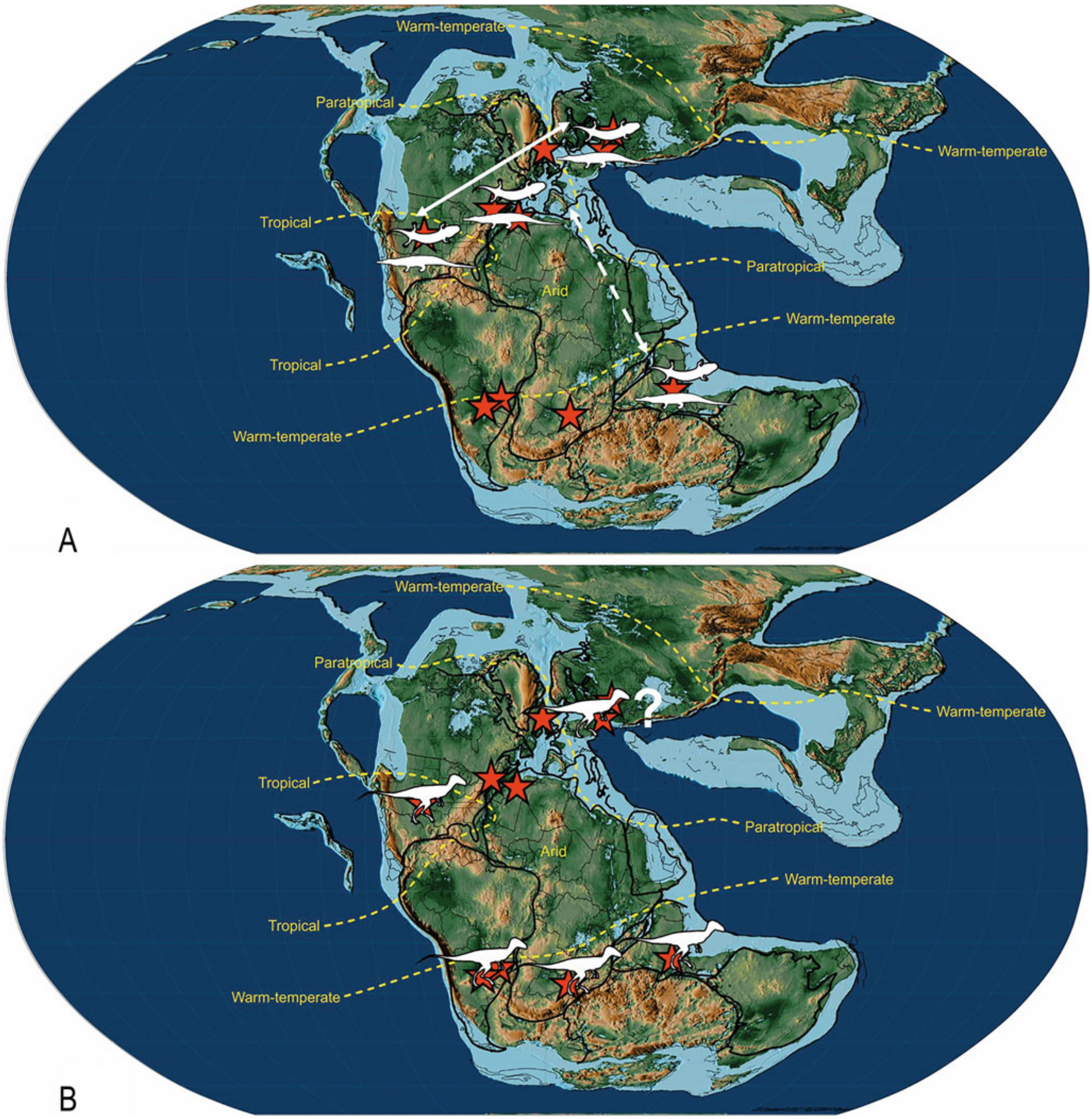


Fig. 8.2 The Late Carnian-Norian paleogeographic map, displaying the radiation of tetrapods; locations of fossil sites of Late Triassic tetrapods are shown by orange stars. **A**, semiaquatic phytosaurs and metoposaurs showing some degree of provincialism; and **B**, early dinosaurs. Among Gondwana continents, only India and Morocco had yielded phytosaur-metoposaur assemblage, which is common in Laurasia. For early radiation of dinosaurs, southern Gondwana such as Argentina and India might be the centers of their origins. Dinosaurs were rare in the early Late Triassic. (courtesy Volkan Sarigul)

The beginning of dinosaur evolution is currently known from the Carnian stage of the Late Triassic (about 230 million years ago) Gondwana beds of Argentina (Ischigualasto Formation), Brazil (Santa Maria Formation), Zimbabwe (Pebbly Arkose Formation) and India (Lower Maleri Formation). By the Carnian stage, dinosaurs had diversified into three major lineages, Ornithischia, Sauropodomorpha, and Theropoda—with different dietary behaviors and modes of locomotion, and by the Norian stage (around 208 million years ago), some dinosaur groups had become species-rich

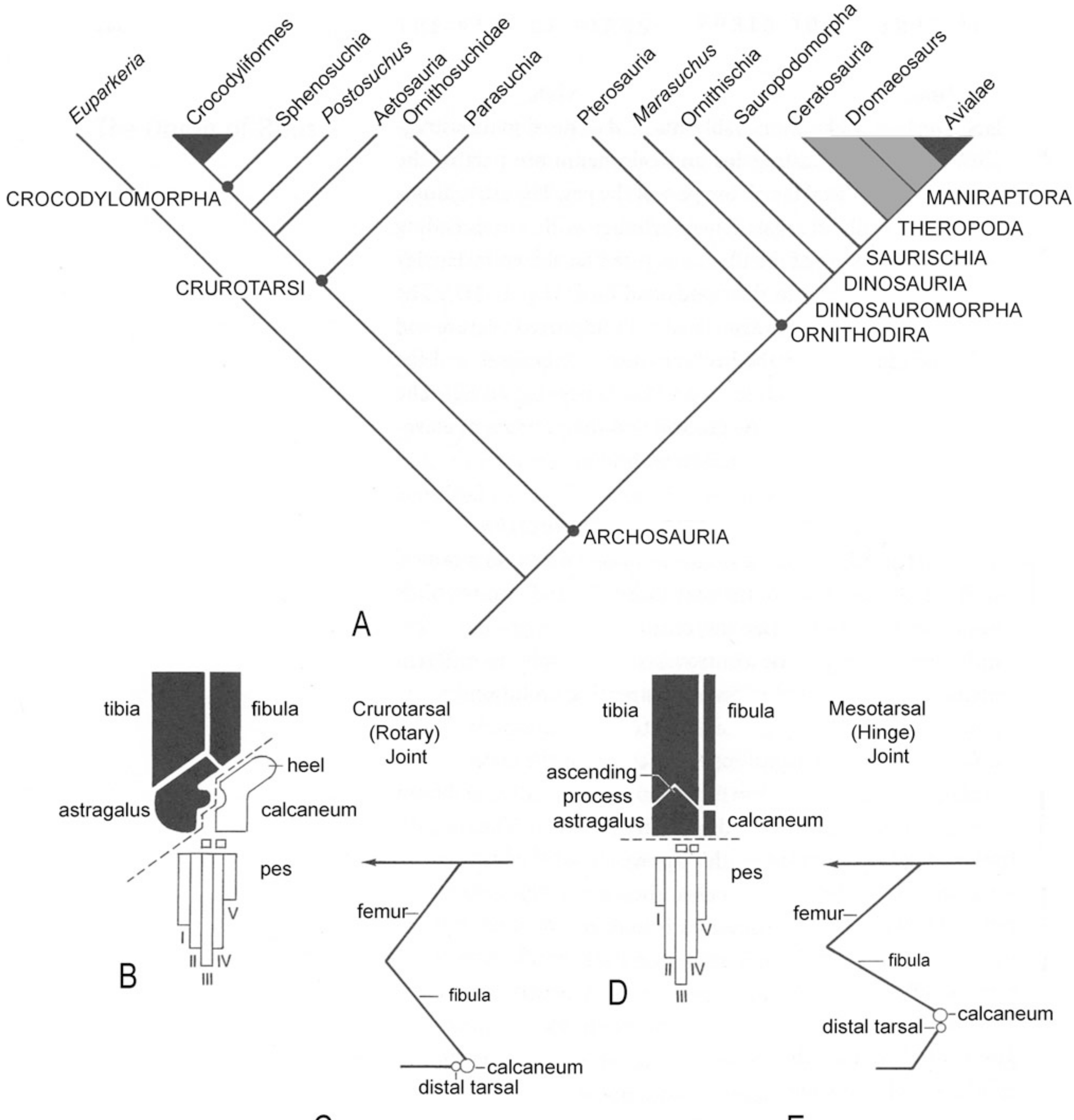


Fig. 8.3 The phylogeny of archosaurs. **A**, cladogram showing the postulated relationships of the basal dichotomy of archosaurs into Crurotarsi (leading to crocodilians) and Ornithodira (leading to birds); **B**, the crurotarsal ankle joint, in which the astragalus forms part of the crus, but the calcaneum, distal tarsals, and combined metatarsals move as a unit on the astragalus and fibula. The peg-and-socket joint between the astragalus and calcaneum allows rotary motion between them; **C**, schematic lateral view of the hindlimb of the Crurotarsi showing the primitive, plantigrade pose; **D**, the characteristic hinge joint of Ornithodira between the proximal and distal rows of the tarsi. The astragalus has a typical ascending process for locking the tibia; the calcaneum is reduced; **E**, schematic lateral view of the hindlimb of the Ornithodira showing improved posture and the digitigrade pes

and numerically abundant. By the end of the Triassic, dinosaurs had also diversified into relatively large, plant-eating forms such as basal sauropodomorphs.

Here I describe the early dinosaurs from India from three successive horizons: a rhynchosaur-dominated Lower Maleri Formation, an archosaur-dominated Upper Maleri, and the

Lower Dharmaram Formation with abundant basal sauropodomorphs but rare theropod members. Similar Late Triassic assemblages occur in the coeval beds of Argentina, Brazil, and Europe, but contrast sharply with North American faunas.

Discovery of Indian Dinosaurs

These are exciting times in vertebrate paleontology, heralding a dinosaur renaissance. So many new discoveries are being made across the globe—from North America, Europe, South America, China, Mongolia, Africa, Australia, and Antarctica; so many new ways of looking at fossils are being devised. The dinosaur fossils of India have much to contribute to the fervor. This is why it is so exciting for me to write this paper. Our story begins with vertebrate collecting in independent India and with the people who did the digging.

In my formative years, I joined the Indian Statistical Institute (ISI) as a Research Scholar in 1964 to work with the British paleontologist Pamela Robinson of University College London, who was a Visiting Professor and scientific advisor at the Geological Studies Unit of ISI. Dr. Robinson was invited through the influence of her mentor and famous geneticist J. B. S. Haldane, who at that time relinquished British citizenship and joined ISI. ISI is a world-renowned academic institution devoted to the research, teaching and application of statistics, mathematics, computer sciences, natural sciences, and social sciences. Dr. Robinson established the Geology unit at ISI and created an integrated research program to foster the study of vertebrate paleontology of the Gondwana formations and disseminate the knowledge (Fig. 8.4A, E). She mentored and influenced other vertebrate paleontologists at the department including Sohan Lal Jain, Tapan Roy Chowdhury, T. S. Kutty, and me. She taught us how to explore new fossils sites by systematic excavation, to record the field data, to map the Gondwana formations, to study the environment of deposition, and to delve into scientific potential, significance, and uniqueness of Indian dinosaurs in paleobiogeography and evolution. Her confidence in our ability ignited our enthusiasm. Sacrificing her own research, she chose to share with us her dream of creating an Indian center for natural history. When I became her Research Associate at the University College, London I got to know Dr. Robinson's vision, dreams, research, scientific rigor, and frustrations more closely. Dr. Robinson began the renewal of vertebrate paleontology in newly independent India. During that time, the Geology Unit of ISI became a vital research center, stimulating an intellectual resurgence for paleontology. Many famous paleontologists from America such as Alfred S. Romer of Harvard University (Fig. 8.4C, E) and Edwin S. Colbert (Fig. 8.4D) from the American Museum of Natural History visited our unit, gave seminars, studied fossil collections, shared their insights, and participated in fossil excavation. It was a golden age of vertebrate paleontology in India. Although most of the ISI paleontologists mentioned above are no longer with us, the tradition is continued today by Saswati Bandopadhopadhya, Dhurjati Sengupta, and subsequently their students, who made, and continue to make important strides in vertebrate paleontology research.

Soon after, two other centers—Geological Survey of India and Panjab University—began the systematic collection of vertebrate fossils from the Gondwana formations, following in the footsteps of ISI. From GSI, P. M. Datta, D. M. Mohabey, Z. G. Ghevariya, P. P. Satsangi, and P. Yadagiri made significant contributions to the discovery of vertebrate fossils. Similarly, my good friend Ashok Sahni would inspire and guide the outstanding young graduate students in Panjab University in vertebrate paleontology (Fig. 8.4B). Some of his students including Guntupalli Prasad, Sunil Bajpai, Ashu Khosla, K. Kumar, R. S. Loyal, and R. S. Rana would continue his legacy in vertebrate paleontology. This paper is a tribute to Ashok Sahni for his great contribution and dedication to Indian vertebrate paleontology.

Lower Maleri Formation (Late Carnian-Early Norian)

The first world of Indian dinosaurs began about 230 million years ago in the Upper Triassic Maleri Formation. Early in their history, dinosaurs were small and inconspicuous in the Late Triassic ecosystems. Even though we know a great deal about early dinosaurs from their fossil record in Argentina, such as *Herrerasaurus* and *Eoraptor*, it is not certain that South America was the exact cradle of their origin because they are also found quite early in the Lower Maleri Formation of India during the same time. Most likely, dinosaurs started in Argentina or India and as they dispersed across Pangea, they were evolving into new species. The Maleri is rich in fossils of many kinds. There are plants, together with an abundance of species of various tetrapods. Most importantly for us, there are dinosaurs. In the Lower Maleri Formation, as in other parts of the world, dinosaurs appear to have been minor players on the ecological stage, but by the Upper Maleri time, they became more prominent and numerous.

The Maleri Formation in the Pranhita Godavari Valley of the Adilabad district, in the northern region of Telengana, was known for tetrapod fossils for almost a century (Table 8.1). Vertebrate fossils were collected in 1866 by Reverend Stephen Hislop of Nagpur, and later on by the

Fig. 8.4 Visiting scientists and resident paleontologists at the Geological Studies Unit of the Indian Statistical Institute in early 1970s. **A**, Pamela Robinson; **B**, Ashok Sahni; **C**, Alfred Sherwood Romer and author; **D**, the author and Ned Colbert; **E**, Geology Museum of the Indian Statistical Institute, Kolkata, during the visit of Alfred Sherwood Romer of Harvard University. At the background, partial skeleton of the Kota sauropod *Barapasaurus* and a mounted skeleton of a Maleri rhynchosaur *Hyperodapedon* (at the center); from left to right: 1, Tapan Roy Chowdhury; 2, Al Romer; 3, the author; 4, Pamela Robinson; 5, Sohan Lal Jain; 6, T. S. Kutty. Other paleontologists in the figure came from the Geological Survey of India and University College, London

members of the Geological Survey of India (GSI), mostly as surface finds. The whole GSI collection of the Maleri fossils was sent to the famous German paleontologist Frederick von Huene of Tübingen University, who had worked with similar fossils from Brazil and East Africa. Huene (1940) described the fragmentary remains of the Maleri vertebrates such as metoposaurs, rhynchosaurs, and phytosaurs in the Memoirs of the Geological Survey of India.

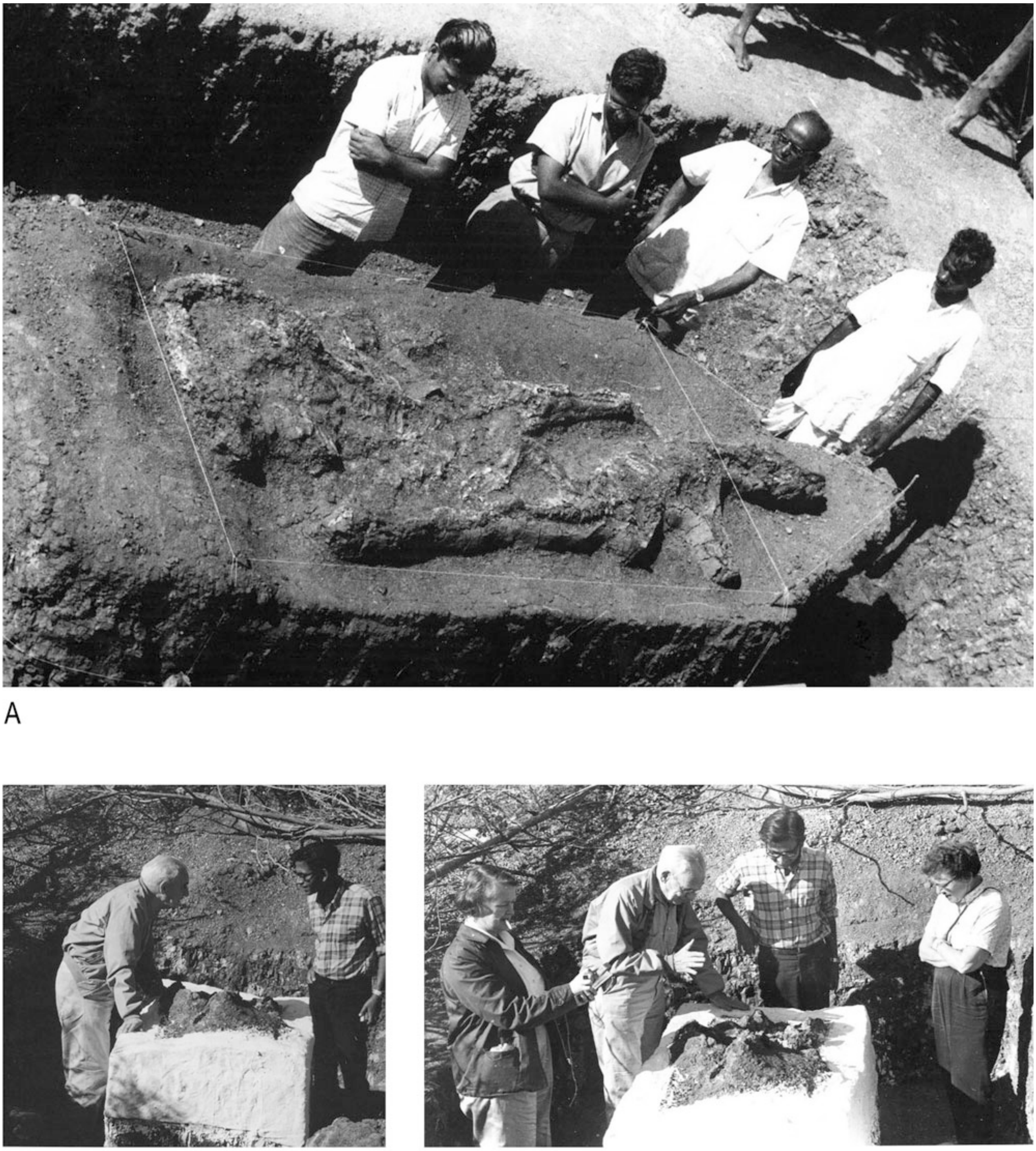
Dr. Pamela Robinson suggested that I begin field work in the Lower Maleri Formation in Adilabad district of Andhra Pradesh, looking there for vertebrate fossils as part of my dissertation project. Huene's memoir was my guide in searching out the old fossil localities. On my first field trip in the Pranhita-Godavari Valley, I was mesmerized by the stark beauty of the landscape of the Maleri Formation. The redbeds there rise – a rainbow spectacle of red, white, yellow, lavender, and blue in the badlands, ablaze with dramatic light and color. Here in these redbeds, in the very first field season, I discovered several associated skeletons of rhynchosaurs, *Hyperodapedon huxleyi*; one such complete skeleton was mounted at the Geology Museum of ISI (Fig. 8.4). During repeated field works in this area, I had the pleasure and thrill of discovering other spectacular skeletons of fossil tetrapods from the Lower Maleri Formation including malerisaurids, phytosaurs, cynodonts, and their relatives, which are currently housed at the Geology Museum of ISI. The most common tetrapods include a metoposaurid tetrapod *Metoposaurus* (Roy Chowdhury, 1965), a protorosaurid *Malerisaurus robinsonae* (named in honor of Dr. Robinson; Chatterjee, 1980), an archosauromorph *Hyperodapedon* (Chatterjee, 1974), a phytosaur *Parasuchus* (Chatterjee, 1978a) (Fig. 8.5), and a cynodont *Exaeretodon statisticae* (named in honor of Indian Statistical Institute; Chatterjee 1982b).

One predatory dinosaur *Alwalkeria maleriensis* is one of the earliest known dinosaurs in the world, lived in the Maleri ecosystem around 230 million years ago (Chatterjee 1987). I named the genus *Alwalkeria* in honor of my former mentor Alick Walker of the University of Newcastle upon Tyne, England, who pioneered and advanced the field of archosaur anatomy. *Alwalkeria* was a small, lightly-built, gracile theropod, like *Eoraptor* of Argentina, and would be about 1.5 m long with an estimated weight of 5 kg. The partial skull of *Alwalkeria* is about 4 cm long, with a subnarial fossa, and the jaws were equipped with sharp, conical heterodont teeth. The hind foot suggests its cursorial adaptation. *Alwalkeria* was relatively small compared to its contemporary archosaurs in the Maleri ecosystems such as phytosaurs and rauisuchians, but fleet-footed. In size and proportion, *Alwalkeria* is comparable with *Eoraptor* of the Ischigualasto Formation of Argentina. The premaxilla is loosely attached to the maxilla but interrupted by a subnarial fossa; and the maxilla shows deep antorbital fossa. Except for some small nipping teeth at the front, all other teeth of *Alwalkeria* were recurved, sharp but unserrated, excellent for capturing small prey and insects. The lower jaw was fused at the front with a symphysis, allowing to move upper and lower teeth against each other in orthal motion. Perhaps *Alwalkeria* fed on carrion or small vertebrates (Fig. 8.6).

In 1970, I wanted to explore the Late Triassic Tiki Formation in the Rewa Basin of the Son-Mahanadi Valley in central India, which is coeval with the Lower Maleri Formation and has yielded typical Maleri fauna such as rhynchosaur-phytosaur-metoposaur assemblage. At that time, the famous vertebrate paleontologist from Harvard University, Professor Alfred Sherwood Romer and his wife Ruth were visiting ISI. Pamela Robinson brought Dr. and Mrs. Romer to my field area, where they stayed for a week to participate in the field work; in the evenings, sitting around the campfire we sampled the local mohua brew, which inspired stories from Romer late into the night. It was a memorable experience to hear Romer narrating his expeditions in South America and Texas and his insights in vertebrate paleontology and evolution. At the time, I was excavating an articulated skeleton of a new rauisichian from the Tiki Formation with Pranab Majumdar. Romer offered valuable suggestion in the field during excavation (Fig. 8.5 B, C). Later I christened the name of this Tiki rauisuchian as *Tikisuchus romeri* in honor of Prof. Romer (Chatterjee and Majumdar 1987). *Tikisuchus* was the top predator in the Tiki and Maleri ecosystems, overshadowing the emerging dinosaurs such as *Alwalkeria*.

Upper Maleri Formation (Late Norian)

My colleague at the Indian Statistical Institute (ISI), T. S. Kutty was a prolific fossil hunter (Fig. 8.4). While I was prospecting the Lower Maleri Formation, Kutty was engaged in mapping and collecting the Upper Maleri and Dharmaram formations in adjacent areas of Adilabad district and there discovered a series of amazing early dinosaur remains. He never got a chance to publish these specimens. Before his retirement, he handed over to me all the dinosaur specimens he had collected for collaborative works. Since spectacular specimens of early dinosaurs are known from the Late Triassic Gondwana beds of Argentina, I invited my Argentinean colleagues Fernando Novas and his student Martin Ezcurra to study and compare Indian specimens with those of Argentina. The detailed study of the Upper Maleri dinosaurs and their phylogenetic relationships filled a major gap in the early history of dinosaur radiation (Novas et al. 2011). The typical Lower Maleri tetrapods such as rhynchosaur *Hyperodapedon*, protorosaur *Malerisaurus*, phytosaur *Parasuchus*, and cynodont *Exaeretodon* apparently



A B C

Fig. 8.5 Field photographs in the Late Triassic Maleri and Tiki formations during excavation. **A**, Dhuiya Pradhan, the author, driver, and a local field guide watching two articulated skeletons of the Maleri phytosaur *Parasuchus*. Inside each skeleton of *Parasuchus* in the stomach region, undigested remains of a prey *Malerisaurus* were found; **B**, Al Romer and the author in the Tiki field look at the newly discovered rauisuchian skeleton *Tikisuchus*; **C**, Pamela Robinson, Al Romer, the author, and Ruth Romer discuss on *Tikisuchus*, the largest predator in the Triassic

disappeared in the transition time between the Lower and Upper Maleri formations. The Upper Maleri dinosaur fauna includes three basal sauropodomorph dinosaurs: an unnamed guaibasaurid (ISI R277), a nonplateosaurian *Nambalia roychowdhurii* and a plateosaurian *Jaklapallisaurus asymmetrica*, thus suggesting that India may be an important center

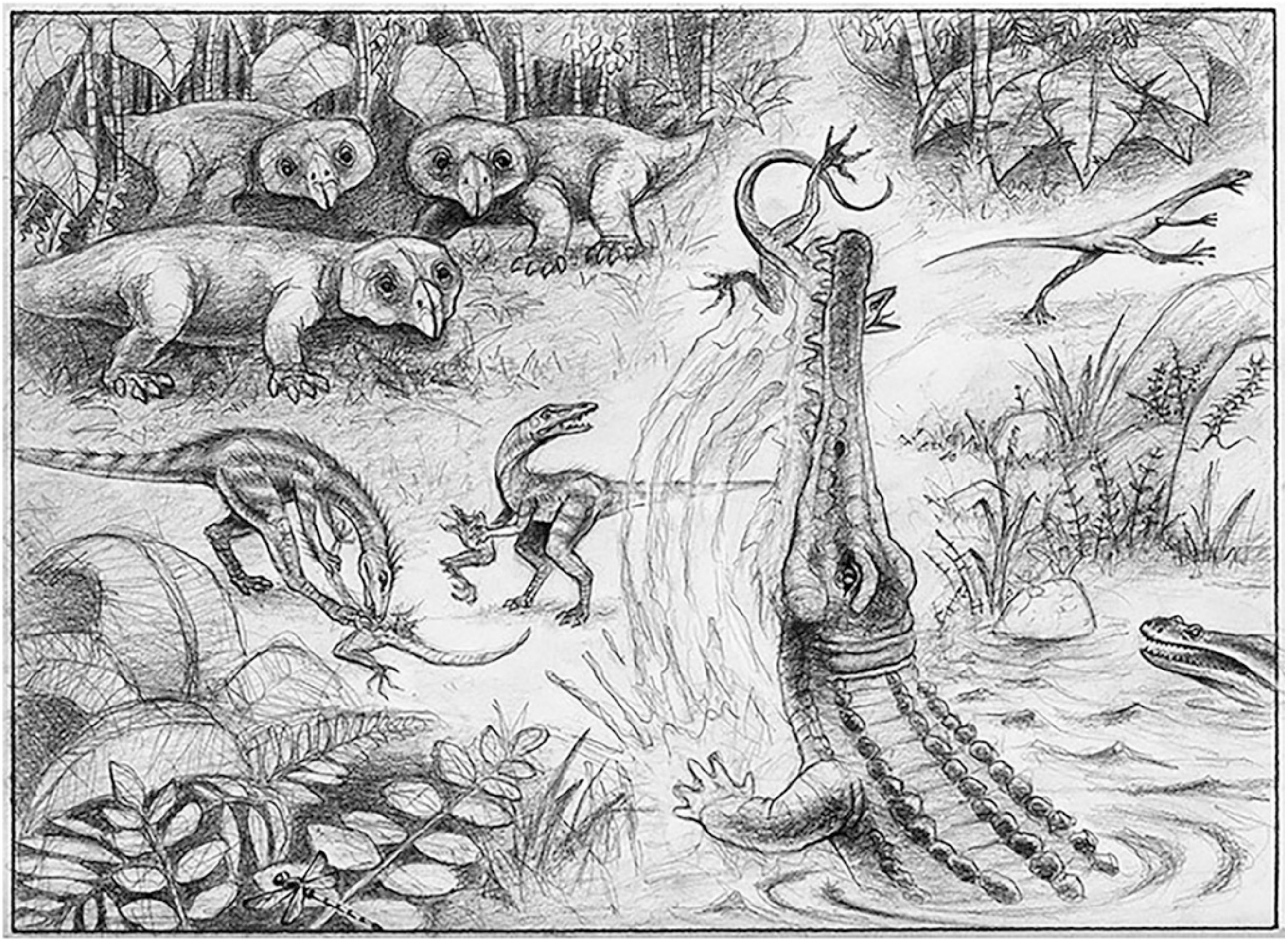


Fig. 8.6 Paleoecology of the Late Triassic tetrapods from the Lower Maleri Formation. At the back, three individuals of *Hyperodapedon* startled by the violent action of gharial-like *Parasuchus*, seizing a *Malerisaurus*, while her mate flees to the right. At the middle, two individuals of theropod dinosaur *Alwalkeria* devouring a baby of *Malerisaurus*. In the water, in the far right, a salamander-like *Metoposaurus* is cautiously watching the predation of *Parasuchus* (after Chatterjee et al. 2017)

for the origin and early radiation of sauropodomorph dinosaurs. The specific name of *N. roychowdhurii* is given in honor of our colleague at ISI, Tapan Roy Chowdhuri (Fig. 8.4). The phylogenetic relationships of the Late Triassic Maleri dinosaurs are shown in a simple cladogram highlighting the Maleri taxa (Fig. 8.7).

Two unnamed basal dinosaurs are fragmentary. ISI R282 is represented by two sacral vertebrae, a proximal caudal, a perforated right ilium, proximal and distal ends of the right pubis, and a probable left pubis. Some elements resemble those of the basal dinosaurs of Argentina such as *Staurikosaurus* and *Herrerasaurus*, other characters are unique to this taxon. ISI R284 is represented by a solitary right ilium, showing some dinosaurian hallmarks such as perforated acetabulum, highly arched dorsal margin of the iliac blade, and the preacetabular process which is strongly compressed transversely. Because of the fragmentary nature, both specimens are difficult to diagnose.

The dinosaurs from the Upper Maleri Formation are dominated by basal sauropodomorphs. The basal sauropodomorphs have been found in all continents including Antarctica and are common in the Norian beds of Argentina (*Coloradosaurus*, *Mussasaurus*, *Riojasaurus*) and Germany (*Sellosaurus*, *Efraasia*, *Plateosaurus*, and *Ruehleia*). ISI R277 is very similar to *Guaibasaurus*, a primitive saurischian dinosaur from the Early Norian Caturrita Formation of Brazil. *Guaibasaurus* is known from a partial skeleton and appears to be more closely related to sauropodomorphs than theropods. It was a bipedal dinosaur around 2 m long, with short, sharply clawed forelimbs but its affinity is controversial. Bonaparte et al. (2007) concluded that a combination of several postcranial features distinguishes *Guaibasaurus* from all other dinosaurs, and it is closely related with *Saturnalia*. The Maleri specimen is represented by several postcranial elements, which compare well with those of *Guaibasaurus* and was allocated in the same family

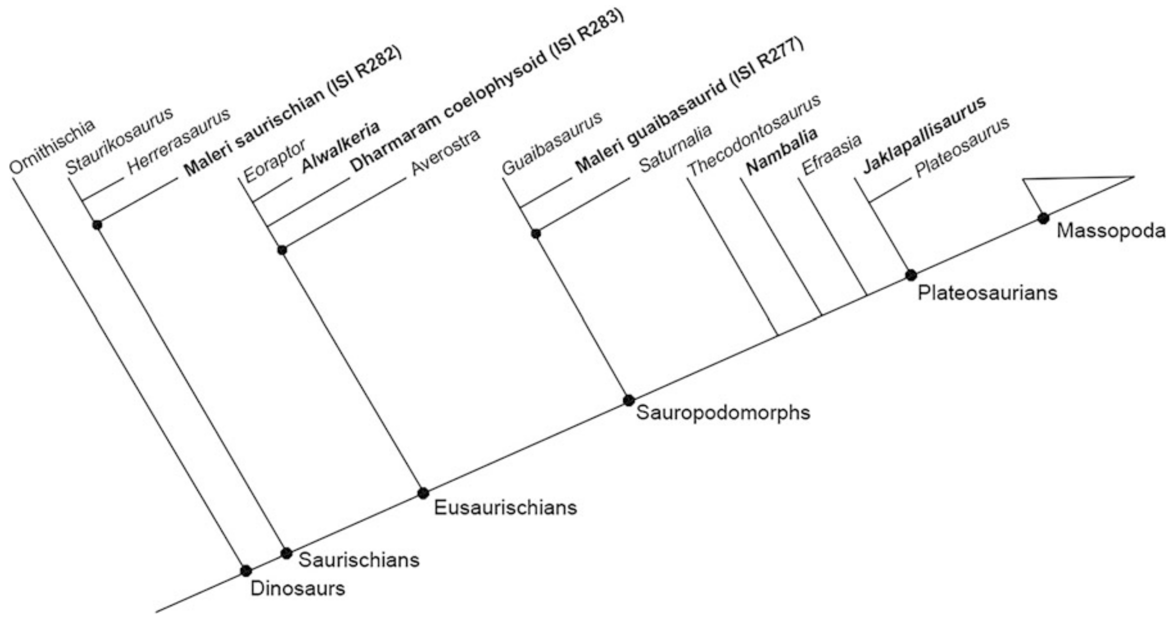


Fig. 8.7 Cladogram showing the origin and early evolution of dinosaurs during the Late Triassic of India. Indian taxa are shown in bold fonts

of Guaibasauridae (Novas e al. 2011). In our phylogenetic analysis, the Maleri guaibasaurid appears to be a stem sauropodomorph and a sister-group of *Nambalia* (Fig. 8.7).

Two distinctive basal sauropodomorphs are represented by *Nambalia* and *Jaklapallisaurus* respectively, which are more derived than *Guaibasaurus*. *Nambalia* is known from partially articulated postcranial material. It is a basal sauropodomorph dinosaur that shows several autapomorphies in femur and astragalus morphology. It is more derived than *Thecodontosaurus* of England but closely related to *Efraasia* of Germany (Fig. 8.7). *Nambalia* was a lightly built, small-sized, herbivorous quadrupedal sauropodomorph, about 3 meters long. *Jaklapallisaurus* is more derived than *Nambalia*, and is a plateosaurian sauropodomorph dinosaur, known from postcranial material and closely resembles *Plateosaurus* from Germany (Novas et al. 2011). *Jaklapallisaurus* was a medium-sized sauropodomorph, lightly built, about 4 meters long. *Nambalia* and *Jaklapallisaurus* were the first large herbivorous dinosaurs in India that probably lived in herds and their size gave them a larger range of plants on which to feed (Fig. 8.8).

Lower Dharmaram Formation (Rhaetian)

The vertebrate fauna of the Lower Dharmaram Formation is represented by pseudosuchians such as aetosaurs and advanced phytosaurs, which died out at the end-Triassic extinction (Kutty and Sengupta 1989). The dinosaurs are represented by fragmentary remains of sauropodomorphs and neotheropods. Some elements of sauropodomorphs (ISI R279, 280, 281) resemble *Jaklapallisaurus* among basal sauropodomorphs. An isolated femur with a strongly inturned head (ISI R283) is reminiscent of neotheropods such as *Coelophysis*. The Dharmaram coelophysoid can be excluded from Averostra because it lacks a proximally well-developed anterior trochanter extending beyond the level of the ventral margin of the femoral head. All neotheropods became extinct at the end of the Triassic Period except for Averostra (Novas et al. 2011).

The Lower Dharmaram Formation yielded the last vestiges of crurotarsan assemblage including phytosaurs (*Nicrosaurus*) and aetosaurs (*Desmatosuchus* and *Paratypothorax*) before their final exit at the end-Triassic extinction. The Triassic-Jurassic boundary lies between the Lower and Upper Dharmaram formations marking the end-Triassic mass extinction event about 201 million years ago.

End-Triassic Mass Extinction Event

At the end-Triassic mass extinction, most of the non-dinosaurs died out, but dinosaurs were unscathed. On land, all archosaurs other than crocodylomorphs and Avemetatarsalia (pterosaur and dinosaurs), some remaining theropods, and many large tetrapods became extinct. This extinction event vacated terrestrial ecological niches, allowing the dinosaurs to assume the dominant role in the Jurassic period. The cause of the end-Triassic extinction is a matter of considerable debate. The extinction event is typically attributed to climatic changes associated with the

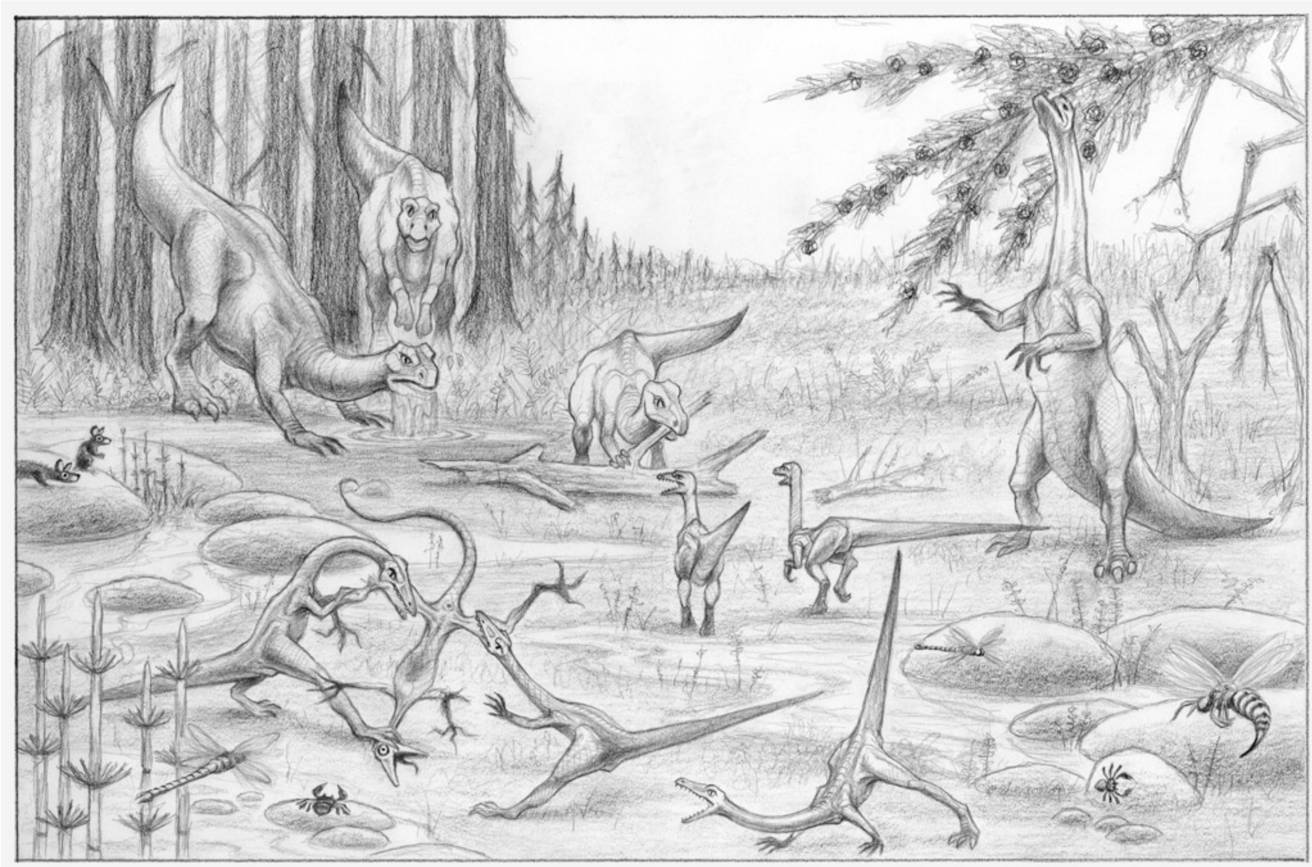


Fig. 8.8 Paleoecology of the Late Triassic dinosaur community in the Upper Maleri landscape. In the foreground is a small herd of five predatory dinosaurs similar to *Coelophysis*, three are engaged in dividing a vulnerable prey, while two other wanders in search of further opportunity. In the background left two herbivorous sauropodomorphs *Jaklapallisaurus* emerge from the *Araucarioxylon* forest: one stoops to drink from a pool of water while the other watches with mild interest the conflict in the foreground. On the far right, standing on hind legs, a sauropodomorph *Nambalia* stretches to get at leafy vegetation. Crouched in the center is a small guaibasaurid munching on a fallen conifer tree, inciting the curiosity of the two wandering *Coelophysis* type dinosaurs. On the extreme left two small mammals squat on a river stone

degassing of basaltic flows from the massive volcanism of the Central Atlantic magmatic province (CAMP) during the initial rifting of the Pangea (McHone 2003).

The victims of this end-Triassic mass extinction included therapsids and largely crurotarsan archosaurs such as phytosaurs, aetosaurs, and rauisuchians that moved slowly. It is intriguing why dinosaurs, who kept a low profile during the Late Triassic, survived the end-Triassic extinction and went on to dominate terrestrial fauna during the Jurassic and Cretaceous periods. Certainly, the bone histology of dinosaurs indicates rapid growth, and perhaps high metabolic activity (Padian et al. 2001). During the end-Triassic global warming, food became scarce for all the animals, including the dinosaurs. But early on dinosaurs adapted important anatomical features such as improved posture and gait, and high metabolic activity that may have prepared them during the climatic crisis, giving them greater mobility for long-distance travel in search of food. Due to scarcity of vegetation and decline of prey population, competition for available food resources became severe, and the balance of power shifted from crurotarsan archosaurs to dinosaurs. In this power vacuum, dinosaurs emerged as the winner by default, becoming the great, terrifying giants that ruled the Jurassic and the Cretaceous worlds.

Day: Triumph of the Dinosaurs in the Jurassic

Dinosaurs survived the end-Triassic catastrophe and rebounded with new vigor. Pangea was largely intact during most of the Jurassic Period, allowing dispersal of dinosaurs unhindered across the globe. In the Early Jurassic, dinosaurs came to dominate every niche on land. While sauropodomorphs were still the dominant herbivores, the giant sauropods began to take their place. The descendant of Triassic *Coelophysis*, the Averostra, grew into powerful

predators. The Jurassic Period was the time of the titans, particularly during the latter part. Many new dinosaurs emerged in great numbers and varieties, both carnivores and herbivores. Among them were stegosaurs, brachiosaurs, camarasaurs, allosaurs, and many others. Much of the Jurassic was a warm, moist, hothouse world. The warm, wet climate allowed for the proliferation of lush, green gymnosperm vegetation across the world. On land, dinosaurs and flying pterosaurs dominated the ecosystems, and birds made their first appearance. Early mammals were still small but diversified. Towards the end of the Jurassic Period, the supercontinent began to rift. North America rotated toward the northwest, away from Africa, creating the proto-Atlantic Ocean. Because of the breakup of Pangea, the global climate began to change. The interior of the land masses became more humid and seasonal snow and ice frosted the polar regions. In the Southern Hemisphere, India was in the warm temperate region of Gondwana (Chatterjee et al. 2017). Although Pangea was slowly breaking up, many large landmasses remained intact. As a result, dinosaur communities were similar across the globe.

Upper Dharmaram Formation (Early Jurassic, Hettangian)

In the early Jurassic, the basal sauropodomorphs ('prosauropods') were the dominant herbivores. Gondwana was intact during the Early Jurassic Period (Fig. 8.9). The second phase of dinosaurs on the Indian subcontinent, represented by the Jurassic forms, was not all like the first. The dinosaurs were not the same, the ecosystems were not the same. As the Jurassic progressed, the world became wetter, especially at the higher latitudes and the giant sauropods took over. The Upper Dharmaram Formation contained an abundance of sauropodomorph dinosaurs, but none of the Late Triassic crurotarsans such as phytosaurs, aetosaurs, and rauisuchians survived, thus hinting at the victory of dinosaurs by default. The Upper Dharmaram fauna is comparable to that of the Early Jurassic horizons of the Upper Elliot and Clarens Formation of southern Africa, the Kayenta Formation of Arizona, and the Lower Lufeng Formation of China.

The associated fauna of the Upper Dharmaram Formation consisted of a sphenosuchian crocodylomorph, a neotheropod, and two sauropodomorphs (Chatterjee et al. 2017; Kutty et al. 2007). The sphenosuchian crocodylomorphs were completely terrestrial cursors that interacted with the dinosaurs. The Indian sphenosuchian compares well with *Sphenosuchus* of the Elliot Formation of South Africa, *Kayentasuchus* from the Kayenta Formation of Arizona, and *Dibothrosuchus* from the Lower Lufeng Formation of China. Among dinosaurs both theropods and sauropodomorphs are known. Theropod material is fragmentary, but some elements show striking similarities to those of *Dilophosaurus*, a neotheropod from the Kayenta Formation of Arizona. *Dilophosaurus* measured about 7 m long and weighed about 400 kg.

In honor of our ISI colleagues, I and my two coauthors named and described two sauropodomorphs from the Upper Dharmaram Formation: *Pradhania gracilis* and *Lamplughsaura dharmaramensis*, (Kutty et al. 2007). During our field work in the Pranhita-Godavari Valley, gifted fossil collector Dhuiya Pradhan was our outstanding field assistant (Fig. 8.5A). Dhuiya never went to a school and could barely sign his name, yet he could easily identify every bone in the field. I was always impressed with his anatomical knowledge and his native instinct for finding new fossil sites. We named the genus *Pradhania* in honor of Dhuiya Pradhan. *Pradhania* is known from a few skull elements, vertebrae and hand bones. It was a massospondylid sauropodomorph of modest size, about 4 m long and weighing about 1000 kg, closely resembling *Massospondylus* of South Africa, but more derived than *Riojasaurus* of Argentina (Fig. 8.10).

Similarly, we selected the generic name *Lamplughsaura* in honor of late Pamela Lamplugh Robinson of University College London, our mentor at ISI. *Lamplughsaura* is heavier and larger than *Pradhania* and is known from several partial skeletons (Fig. 8.10). It was a large quadrupedal animal growing up to 10 m long, with a small head, long and flexible neck, powerful limbs, and a long tail. Phylogenetic analysis suggests that *Lamplughsaura* is either a basal sauropod or, less likely, a stem sauropodomorph. It bridges a morphological gap between bipedal plateosaurids such as *Pradhania,* and quadrupedal, long-necked sauropods such as *Kotasaurus* and *Barapasaurus*.

In a poetic twist, it was Pamela who first introduced Dhuiya to paleontological research. While excavating a *Lystrosaurus* skeleton from the Early Triassic Panchet Formation, Pamela noticed one of the village boys watching intently from a distance. She asked if he would like to join the dig, to which he readily agreed. That boy grew up to be Dhuiya, one of the finest fossil collectors in India. The naming of these two dinosaurs from the Upper Dharmaram Formation immortalized this chance encounter of a field scientist and a curious boy (Fig. 8.10).

Lower Kota Formation (Sinemurian-Toarcian)

The Kota Formation in the Pranhita-Godavari Valley conformably overlies the fluvial deposits of the Dharmaram Formation and is unconformably overlain by the Early Cretaceous Gangapur Formation. My ISI colleague Dhiraj Rudra had carefully mapped the Lower Kota Formation and interpreted its depositional history. Rudra (1982) divided the Kota Formation into two lithological units, a lower and an

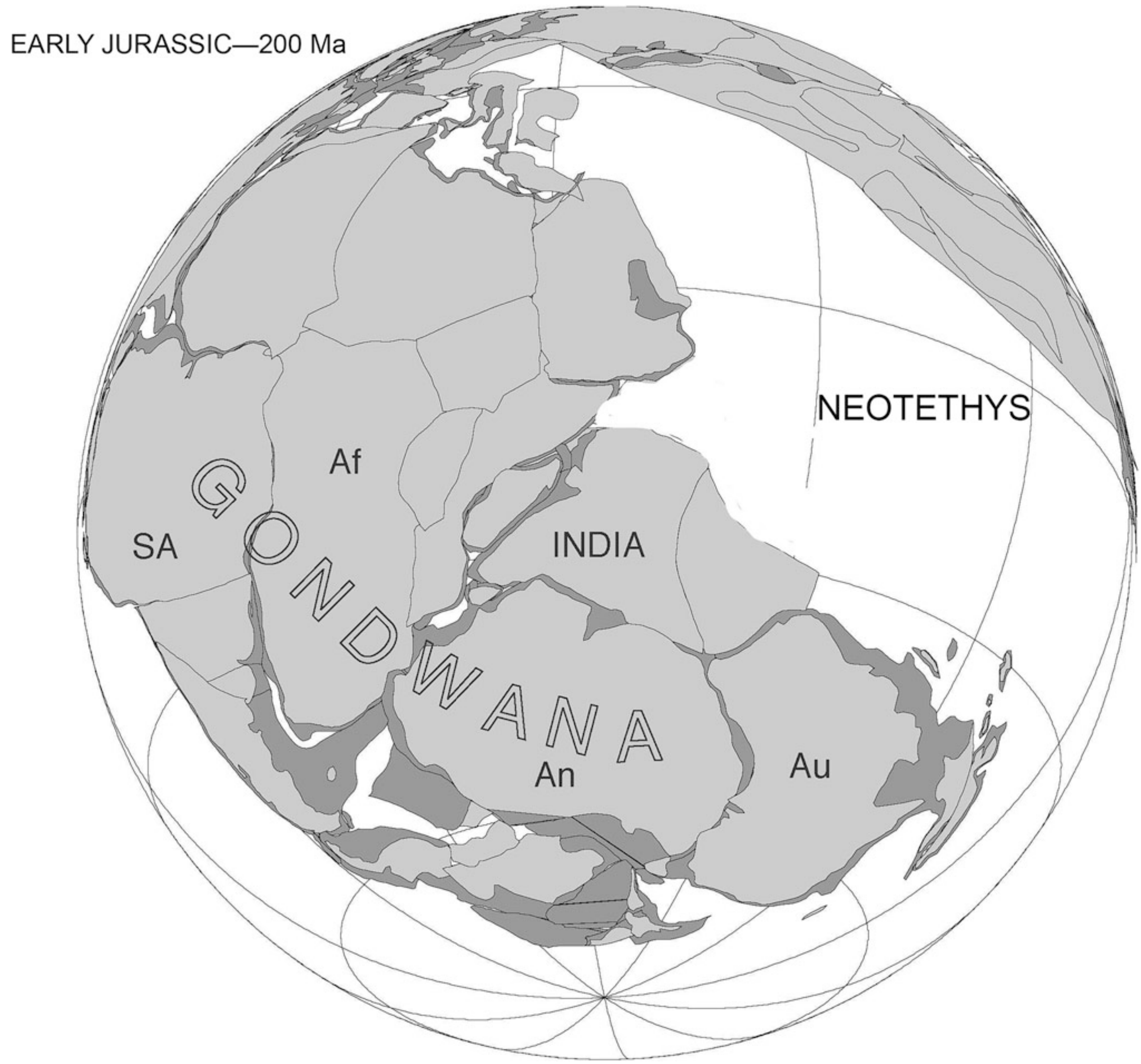


Fig. 8.9 Paleogeographic reconstruction of Gondwana in the Early Jurassic (~200 Ma) (after Chatterjee and Scotese 1999)

upper. The lower unit of Early Jurassic age (Sinemurian through Toarcian), called here the Lower Kota Formation, included 15 to 25-m-thick, hard, compact, poorly sorted, cross-bedded arkosic sandstone, typical of stream channel facies. It hosted a freshwater, lacustrine carbonate deposit interbedded with fluviatile sandstones and mudstones. This sandstone shows a fining upward cycle and grades both laterally and vertically into mudstone of the flood plain deposits that are typical of a meandering river environment. The upper unit, called here the Upper Kota Formation, extends to Middle Jurassic on the basis of palynomorph (Vijaya and Prasad 2001) in age (Aalenian through Callovian), and includes a marl and limestone bed, succeeded by red mudstones of fluvial or flood plain origin. The limestone was deposited in a series of interconnected playa lakes, under a moderately hot climatic regime.

The mudstone of the Lower Kota Formation has yielded a rich assemblage of vertebrates including two early sauropods, three mammals, invertebrates, and charophytes. *Kotasaurus* (Yadagiri 1988, 2001) and *Barapasaurus* (Jain et al. 1975; Bandyopadhyay et al. 2010) represent the early members of two well-known sauropods. The mammalian

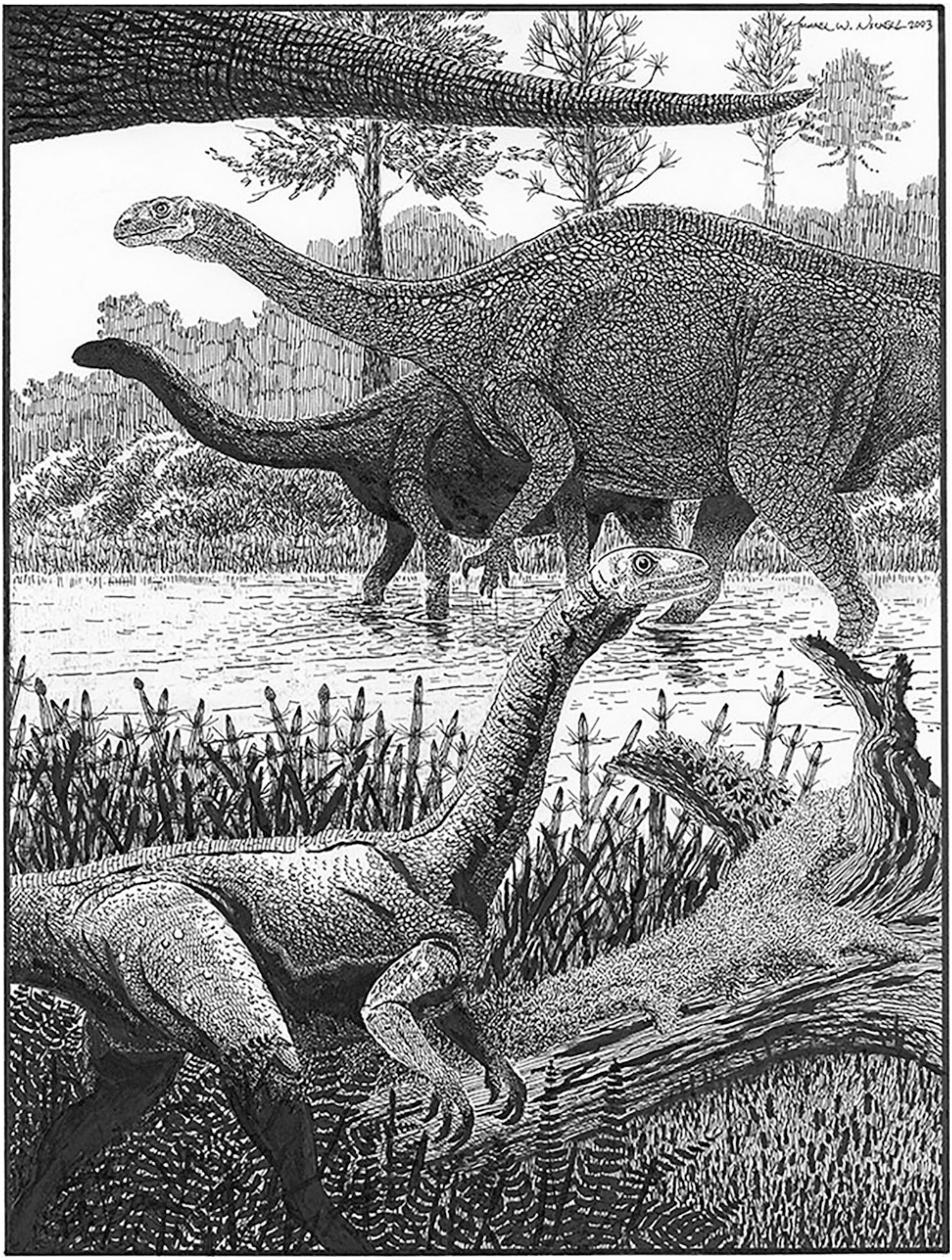


Fig. 8.10 Paleoecology of the Early Jurassic sauropodomorph community in the Dharmaram landscape. In the foreground is the solitary plateosaurid *Pradhania* (adult body length ∼4 m). In the background is a group of stem sauropod *Lamplughsaura* (adult body length ∼10 m) (after Chatterjee et al. 2017)

fauna includes a morganucodont – *Indotherium* Yadagiri, 1984 (=*Indozostrodon* Datta and Das 2001), and a kuehneotherid *Kotatherium* (Datta 1981). These mammalian taxa are small, represented by isolated postcanine teeth.

When I first joined the ISI in 1964, Pamela Robinson invited me to collaborate with other ISI paleontologists Sohan Lal Jain, Tapan Roy Chowdhury, and T. S. Kutty on a recently discovered sauropod dinosaur fauna from the Lower Kota Formation. They discovered a rich layer of monospecific sauropod bone assemblage that had been excavated from an area of 276 m^2 from the Lower Kota Formation; it consisted of approximately 300 postcranial elements and few spoon-shaped teeth of an adult individual near the village of Pochampalli, Sironcha in the Chanda district of Maharashtra. On the basis of 6 left femora, it was estimated that there were at least six individuals. The discovery of the Kota sauropod material ignited the interest in vertebrate paleontology research in India.

The taphonomy of the sauropod bone bed at Sironcha in Maharashtra state is interesting. Apart from one partially associated skeleton, the bones were disarticulated, dispersed, and transported by river current. Mass accumulations of a single species of a sauropod suggest group behavior. The bones of multiple individuals occur in a single bone bed. The absence of delicate elements such as skull material clearly suggests some sort of *post mortem* disturbance during transportation. The limb bones show a preferred NE-SW direction, indicating that the long bones were aligned in response to current flow. However, the state of preservation of the majority of the fossil bones is remarkably good, with very little distortion or abrasion, indicating that the transport of bones was short. The bone bed is reminiscent of a log jam in a river; this is evidenced by the presence of actual logs up to 3 m long along with the bones. The bone assemblage of several sauropod individuals in one place may suggest sudden death due to a catastrophic event such as a flash flood in the flood plain area causing the death of a small herd of sauropods rather than to an attritional event.

The sauropod bones were skillfully prepared by Pranab Majumdar at the Geology unit of ISI for comparative study. Because of the wide publicity of the discovery of the earliest sauropod from India, Edwin H. Colbert from the American Museum of Natural History and his wife Margaret visited our Geology unit in 1964, and went on to Sironcha with the ISI paleontologists to see the Kota sauropod material *in situ,* and to further participate in the digging (Fig. 8.11A, B). Later Colbert wrote a nice account of the Sironcha field trip and the significance of the Kota sauropod in his two memoirs, *A Fossil Hunter's Note B*ook (Colbert 1980) and *Digging into the Past* (Colbert 1988).

The first discovery of a nearly complete dinosaur skeleton from the Kota Formation was a major breakthrough in the understanding and appreciating of Mesozoic terrestrial vertebrates from India; it inspired systematic collecting in other unexplored regions. The dinosaur collection from the Lower Kota Formation included six partial skeletons and many disarticulated bones, which were beautifully preserved. I took part in studying and describing the new sauropod material with my senior colleagues, we named the taxon *Barapasaurus tagorei* (Jain et al. 1975). The generic name "barapa" means 'big legged dinosaur' in Bengali (because the femur was about 1.5 m long); the specific name commemorates the centenary birth of India's Nobel-laureate poet Rabindranath Tagore.

Records of Early Jurassic sauropods are quite rare, often known from isolated fragmentary remains. Represented by nearly a complete postcranial material, *Barapasaurus* fills a major gap in our understanding of the origin and early evolution of sauropod dinosaurs. *Barapasaurus* was hailed as one of the oldest sauropod dinosaurs in the world (Jain et al. 1975), and our paper received national and international media coverage. The whole skeleton of *Barapasaurus* was installed in the Geology Museum of ISI by Pranab Majumdar. It was the first mounted dinosaur skeleton in India (Fig. 8.11C).

Sauropod dinosaurs possess a highly specialized set of skeletal adaptations related to their gigantic size, obligate quadrupedalism, graviportal locomotion, and strictly herbivorous diets that accrued over a 140 million-year history. The sauropod body plan is unique among terrestrial tetrapods, with a short and deep trunk combined with a small skull and very long slender neck and tail, and massive columnar limbs. The earliest diverging forms such as *Lamplughsaura*, *Vulcanodon*, *Kotasaurus*, *Shunosaurus*, *Barapasaurus*, and *Jobaria* are successively closer to Neosauropoda, which includes Diplodocoidea and Macronaria (Wilson 2002).

Barapasaurus was the first to have attained gigantic size, with a body length of 14 m, and the first to be fully quadrupedal, with graviportal and columnar limbs (Fig. 8.12). The skeletal elements of *Barapasaurus* show many primitive characters that are absent in later sauropods. Typical sauropod features of *Barapasaurus* are: the quadrupedal posture with columnar limbs, four coalesced sacral vertebrae with a well- developed sacricostal yoke, low deltopectoral crest of the humerus, absence of olecranon process, triradiating proximal end of the ulna with deep radial fossa, ilium with low and subrectangular ischial peduncle, and ischial shaft equal to pubic shaft (Bandyopadhyay et al. 2010). The most diagnostic features of *Barapasaurus* are present in the vertebral column. The posterior dorsal vertebrae are tall and possess slit-like neural arches; the neural spines are not bifurcated. Gigantism and elongation of the neck were major biomechanical problems of sauropods, which was compensated by complex vertebral pneumacity. This problem was overcome in *Barapasaurus,* through pneumatization of the

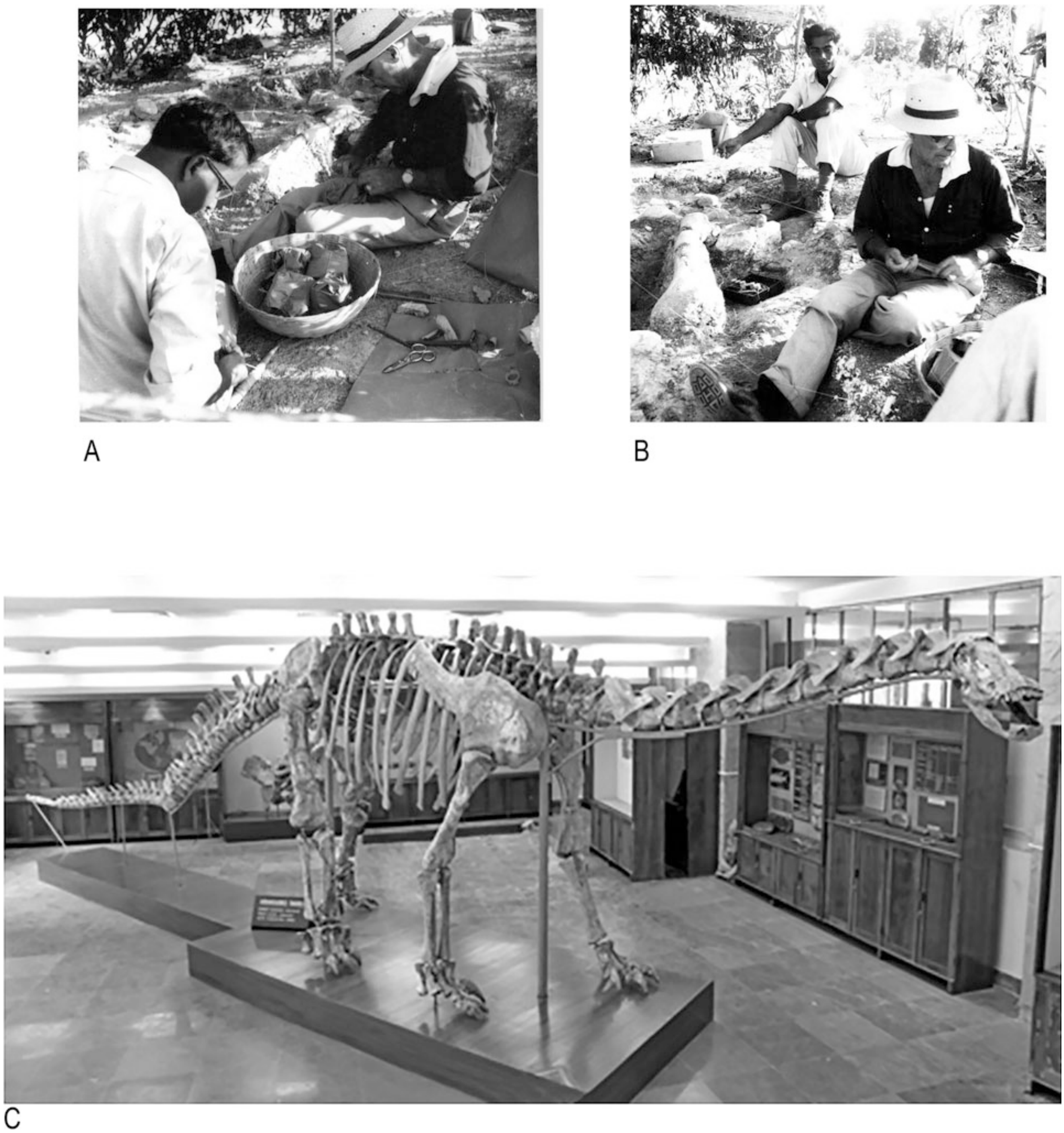


Fig. 8.11 Field photographs in the Early Jurassic Kota Formation during visit of Ned Colbert, excavating the *Barapasaurus* skeleton. **A**, Sohan Lal Jain and Ned Colbert; **B**, Tapan Roy Chowdhury and Ned Colbert; **C**. mounted skeleton of *Barapasaurus* at the Geology Museum of Indian Statistical Institute

centra and neural spines of the cervical and dorsal vertebrae, which significantly reduced the body weight (Jain et al. 1975). Dorsal centra are opisthocoelous. In the hindlimb, the femur lacks the lesser trochanter; the fibula has a broad triangular scar for the tibia; and in the ankle, the astragalus has a posterior fossa, divided by a crest. *Barapasaurus,* a descendant from the Late Triassic dinosaurs of modest size, is a prime example of the fact that certain dinosaurs suddenly became giants in the Early Jurassic. *Barapasaurus* is now considered as a basal member of Eusauropoda, and is more derived than *Vulcanodon* of South Africa and *Shunosaurus* of China (Wilson 2002; Chatterjee et al. 2017).

Kotasaurus yamanpalliensis, from the same horizon of the lower Kota Formation, is a basal sauropod, smaller in size (body length ~9 m) and more primitive than *Barapasaurus tagorei*. It is interesting that two sympatric species of early sauropods lived in central India about 180 million years ago (Fig. 8.12). The bone bed of *Kotasaurus* was first

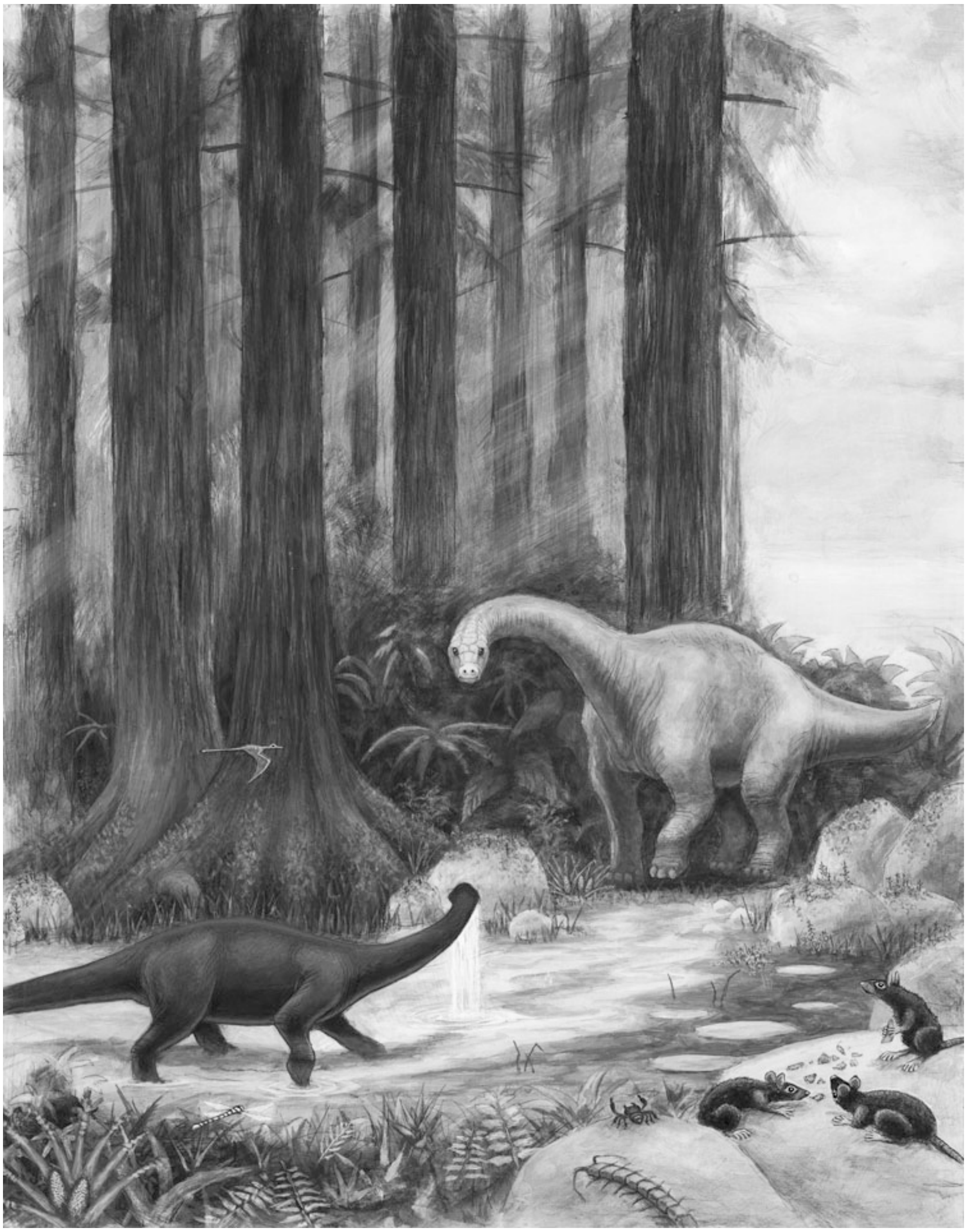


Fig. 8.12 Paleoecology of the Early Jurassic Kota Formation of India. Two basal sauropods, the smaller *Kotasaurus* (front) startled by the arrival of the larger *Barapasaurus* (behind) at the stream. At the lower right foreground, a group of small kuehneotheriid mammal *Kotatherium* look up from their feeding (after Chatterjee et al. 2017)

discovered by my colleague Dhiraj Rudra from the mudstone horizon near the village Yamanpalli, while mapping the Kota Formation. It was however, later excavated and described by P. Yadagiri of Geological Survey of India (Yadagiri 2001). *Kotasaurus* is known essentially from several postcranial skeletons but lacks a skull. It was an obligate quadruped with vertical limbs, and a long neck and tail. A long, low preacetabular process of the ilium, that maintains its dorsoventral width over its entire length, is the diagnostic feature of *Kotasaurus*. The vertebral morphology of *Kotasaurus* is quite different from that of *Barapasaurus*. The vertebrae are massive, without pneumacity. Cervical vertebrae are opisthocoelous, but dorsal vertebrae lack spinal laminae; sacral vertebrae consist of three co-ossified centra; the scapula is tall and has a narrow proximal blade; the humerus is somewhat twisted with a low deltopectoral crest. The femur retains a fourth trochanter. There is a prominent astragalar peg situated anteroventrally.

Upper Kota Formation

The Upper Kota Formation of Middle Jurassic (Vijaya and Prasad 2001) age has yielded a wide variety of small tetrapods including a kayentachelid turtle, two sphenodontids, an iguanian lizard, a pterosaur and seven mammal taxa. A few isolated teeth found in that formation have been attributed to a theropod. A scute and other fragmentary limb bones indicate the presence of a scelidosaurid ornithischian in this formation, but nothing has been diagnosed so far (Chatterjee et al. 2017). Some dental morphotypes of ornithischian and theropod dinosaurs are also known from the upper unit of the Kota Formation (Prasad and Parmar 2020).

Upper Jurassic Bagra Formation

During the Late Jurassic, the vast continent of Pangea started to break up, with narrow Neotethys Ocean dividing it into two landmasses, Laurasia to the north and Gondwana to the south. Gondwana broke apart into two roughly equal parts: West Gondwana comprised South America and Africa, and east Gondwana was composed of Madagascar, India, Australia, and Antarctica (Fig. 8.13). During this period, Earth's climate changed from hot and dry to humid and tropical. On land, dinosaur diversity and scale increased through time, with peaks in the Late Jurassic leading to gigantism. The Late Jurassic formations in many parts of the world have

Fig. 8.13 Paleogeographic reconstruction showing the Bouvet plume and the initial breakup of East Gondwana from West Gondwana in the Late Jurassic (~160 Ma) (after Chatterjee et al. 2013)

produced spectacular dinosaur assemblages including giant sauropods, stegosaurs, allosaurs, and many other forms.

The Late Jurassic sediments remain poorly sampled for dinosaur remains in India. To date, I have found only sauropod remains, probably a titanosaur from the Bagra Formation of Satpura Basin about three decades ago, but the material has yet to be described (Chatterjee and Hotton, 1986).

Origin and Early Evolution of Sauropodomorpha

Sauropodomorpha is a clade of herbivorous dinosaurs that originated during the Late Triassic and were prevalent, both in diversity and giant size, in global terrestrial ecosystems throughout much of the Mesozoic, with at least 175 valid taxa currently known. The earliest members of this group, the basal sauropodomorphs, first appeared in the Ischigualasto Formation of Argentina (Carnian) and achieved a near global distribution by the end of the Triassic. In India, we have several groups of basal sauropodomorphs, as discussed earlier including a Maleri guaibasaurid, a non-plateosaurian *Nambalia*, and the plateosaurian *Jaklapallisaurus* during the Late Triassic. In the Early Jurassic, we encounter a massospondylid sauropodomorph *Pradhania*, and several basal sauropods including *Kotasaurus* and *Barapasaurus* (Fig. 8.14). Thus, the origin and early radiation of sauropodomorphs is nicely documented in the Indian Late-Triassic-Early Jurassic Gondwana sediments. India may be an important center for the origin and early radiation of sauropodomorph dinosaurs.

Evening: Dinosaurs in the Drifting Indian Plate During the Cretaceous

The Cretaceous Period spanned about 80 million years, during which dinosaurs diversified rapidly with the drifting of the continents. During the Early Cretaceous, India began to rift, and drift apart from East Gondwana. The third phase of Indian dinosaurs, in the Late Cretaceous, is quite distinct from the second. It was a different world. During much of the Late Cretaceous, India began to drift northward as an island continent carrying its dinosaur fauna like a passenger ship, until it collided with the Kohistan-Ladakh Arc and incorporated it around 80 million years ago, forming a biotic corridor for dinosaur faunal exchange (Fig. 8.15). The records of dinosaurs from the Post-Gondwana formations of Early Cretaceous sediments of India are essentially blank because of poor sampling rather than for lack of fossil remains. During the Late Cretaceous, dinosaur remains are known from the Nimar Sandstone and the Lameta Formation.

Nimar Sandstone (Cenomanian-Turonian)

In 1996, Ashu Khosla of Panjab University discovered an interesting sauropod bone bed from the Late Cretaceous Nimar Sandstone, in the basal unit of the Bagh Group of Narmada Valley, Central India. Later he and his colleagues described these bones as those of sauropods (Khosla et al. 2003). The material includes limb elements and numerous

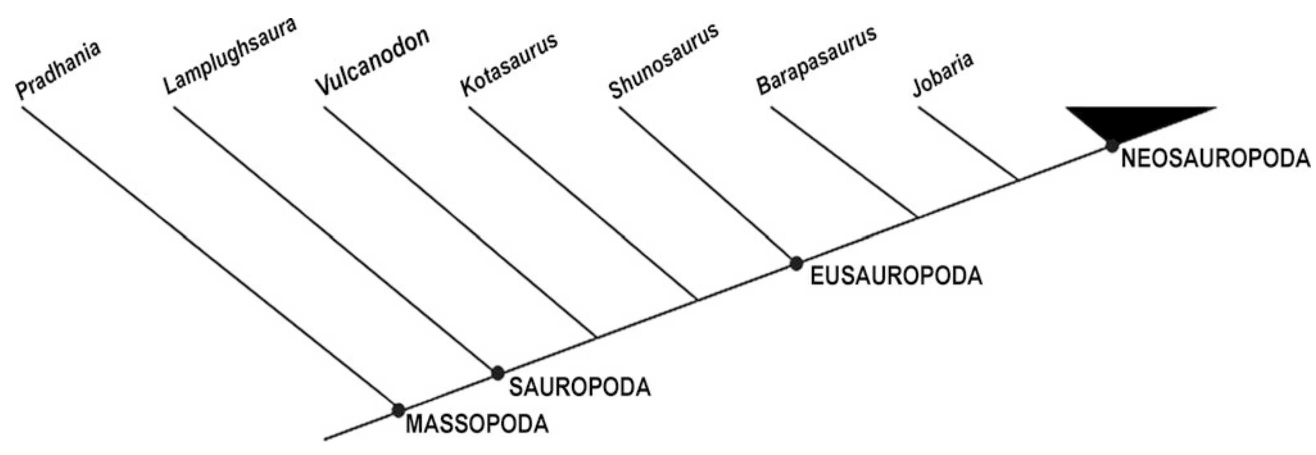


Fig. 8.14 Cladogram showing the origin and early evolution of sauropods during the Early Jurassic of India. Indian taxa are shown by bold fonts (after Chatterjee et al. 2017)

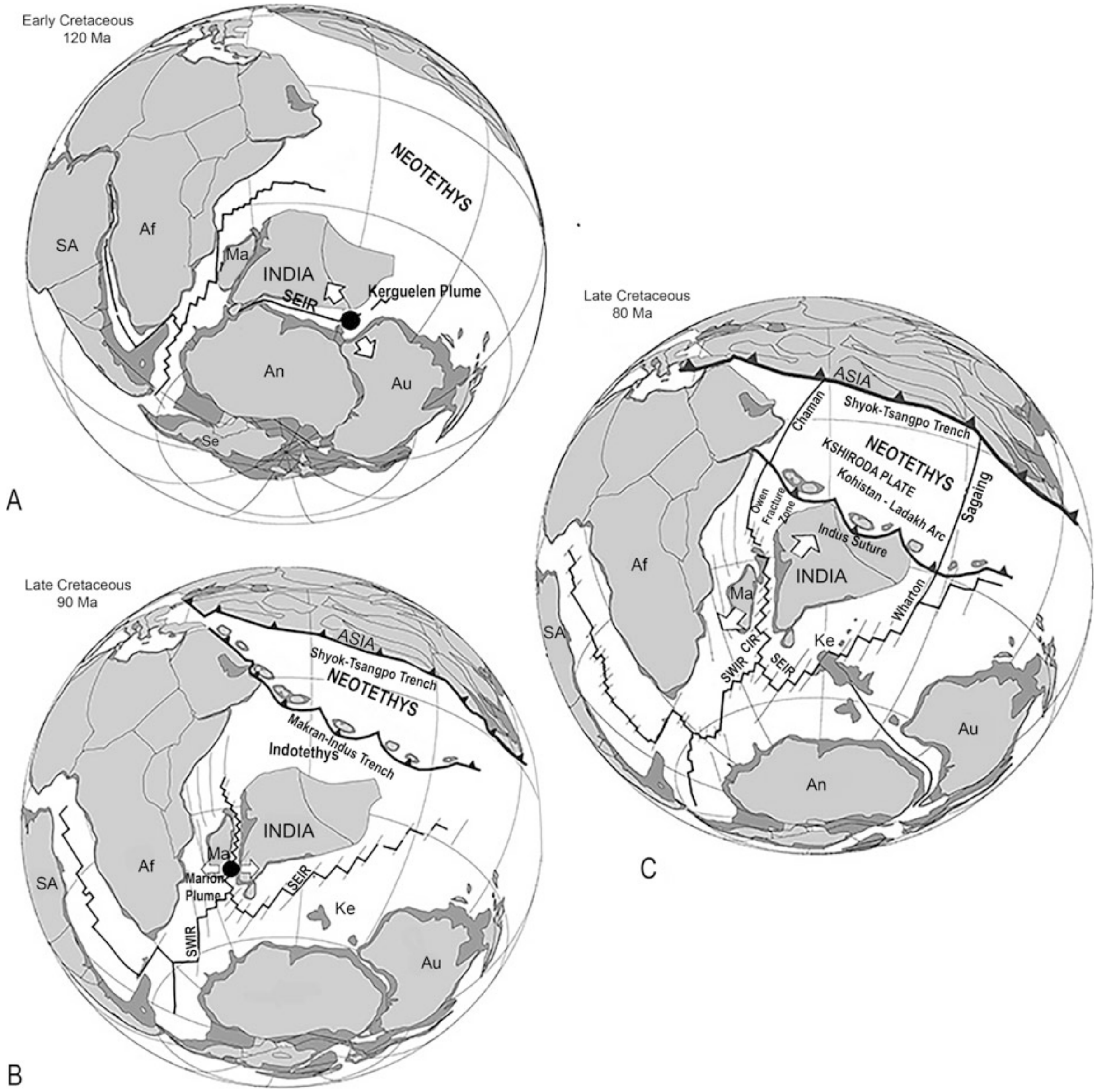


Fig. 8.15 Paleogeographic position of India during the Cretaceous. **A**, the separation of India from Antarctica-Australia in the Early Cretaceous ($\sim$120 Ma) along the Southeast Indian Ridge; **B**, paleogeographic reconstruction of Gondwana fragments during the Late Cretaceous showing the India-Madagascar rift ($\sim$90 Ma) and the location of the Marion plume. India became an island continent during a brief period of Late Cretaceous; **C**, Paleogeographic position of India showing collision of the Indian plate with the Oman-Kohistan-Ladakh (OKL) Arc during the Late Cretaceous ($\sim$80 Ma) time along the Indus Trench. The OKL Arc formed an important corridor for tetrapod migration between India and Africa; other two biotic corridors were: Laxmi Ridge-Seychelles island between India and Madagascar; and emergent Ninetyeast Ridge-Kerguelen Plateau-Antarctica between India and South America (modified from Chatterjee et al. 2013)

fragmentary bones belonging to at least two individuals. Dr. Khosla was kind enough to show me this sauropod material, which looked like a new titanosaur species, perhaps ancestral to the abundant titanosaur remains from the younger Lameta Formation. The Nimar sauropod was a gigantic titanosaur with an estimated length of the femur exceeding >1.5 m. Isolated abelisaurid teeth have also been documented from the green sandstone representing the top most part of the Bagh Group (Prasad et al. 2016).

Lameta Formation (Maastrichtian)

At many places around the fringe of the Deccan volcanic province, fossiliferous sedimentary beds are found associated with the Deccan lava flows. Traditionally, these sedimentary beds are called infratrappean beds (below the basal lava flows, such as the Lameta Formation) or intertrappean

beds (interlayered with lava flows), depending on their physical position with respect to the volcanic flows. The Lameta Formation is a thin but extensive horizon that underlies the basal flows of the Deccan volcanic sedimentary sequences. The Lameta sediments were deposited in an arid terrestrial environment, in a meandering channel. Vertebrate fossils are found in over bank deposits and meander cut-off lakes. The vegetation was sparse with shrub cover near the main stream. The Lameta Formation has yielded one of the finest records of dinosaur bones and nesting sites with fossil eggs and eggshells. On the basis of its stratigraphic position, vertebrate assemblages and associated microfossils such as ostracods, pollens, and charophytes, the age of the Lameta Formation is now considered to be Maastrichtian. The type section of the Lameta Formation is the Lameta Ghat on the banks of the Narmada River near Jabalpur, Madhya Pradesh.

What is particularly interesting from historical point of view is that dinosaurs were known from the Lameta Formation more than two decades before Sir Richard Owen coined the term 'Dinosauria' in 1842, the 'fearfully great lizards.' The Lameta Formation near the city of Jabalpur, central India, is important for the discovery of one the earliest, if not the earliest record of dinosaur remains anywhere in the world. In 1917–19, Charles Matley of the Geological Survey of India (GSI) collected a substantial quantity of sauropod dinosaur material from several localities on the western slope of Bara Simla Hill in the Jabalpur Cantonment area. In 1920, Matley collected additional fragmentary sauropod material from localities in Pisdura in Maharasthra. This material formed the basis of a number of taxa described from the Late Cretaceous of India. Much of the collection went to the British Museum, but the sauropod remains were kept at the Indian Museum in Calcutta (hereafter Kolkata), in the repository of the GSI collection. This remarkable discovery of Indian dinosaur material occurred before the first description of the first dinosaur *Megalosaurus* from the Oxford University campus by William Buckland in 1824. In 1922, the legendary and flamboyant paleontologist Barnum Brown of the American Museum of Natural History (Fig. 8.16A), on the steam ship to India met a vivacious young woman, Lilian, who he wooed and wed in a palm-shaded chapel in Kolkata. The newly-wed couple traveled through different parts of India during their honeymoon, collecting fossils on their way. They collected a great variety of Neogene Siwalik mammals at the foothills of the Himalaya. The trip was chronicled by Lilian Brown in her entertaining book, *I Married a Dinosaur* (Brown 1950). Barnum Brown also visited Matley's site at Jabalpur, collected some skull material of theropod dinosaurs, as well as a dermal osteoderm of a titanosaur, and brought back the material to the American Museum of Natural History, but he never reported the discovery. Soon after Brown's excavation, the army officer Captain W. H. Sleeman (celebrated for eradicating India of its centuries-long-terror of *Thugees*) discovered some dinosaur bones in 1828 from the same fossiliferous site of Barnum Brown at Bara Simla Hill, Jabalpur. The first systematic description of Indian dinosaurs was carried out by Lydekker (1877), who described Sleeman's find from Jabalpur, and ereted a new sauropod taxon *Titanosaurus indicus* on the basis of two procoelous distal caudal vertebrae and an imperfectly preserved femur. Later, Frederick von Huene of Tübingen University was invited to collaborate on the Lameta dinosaurs. Huene and Matley (1933) described the Lameta dinosaur material in a monograph. In 1932–33, Matley collected an additional associated partial skeleton of a titanosaur from the Lameta Formation exposed in the adjacent Chota Simla Hill of Jabalpur, which was sent back to the Natural History Museum (then the British Museum of Natural History); the material was recently described by Wilson et al. (2011) as *Jainosaurus* cf. *septentrionalis*.

I became involved with the Lameta dinosaurs in a strange, roundabout way. My discovery of two nearly complete and articulated phytosaur skeletons, along with their stomach contents (Fig. 8.5A), from the Lower Maleri Formation (Chatterjee 1978a) caught the attention of Professor Joseph T. Gregory, the world authority on phytosaurs, and chairman of the Department of Paleontology at the University of California, Berkeley (Fig. 8.16B). Prof. Gregory kindly invited me to his department as a Visiting Professor in early 1976 to teach vertebrate paleontology, and to compare Indian phytosaurs with North American collection at his museum. I eagerly left India for my new assignment, thus beginning my scientific career in the USA. While at Berkeley, a colleague of mine, Robert Long borrowed Barnum Brown's skull material of the Lameta theropods housed at the AMNH, passing it on to me for study during my stay, since the material was originally from India. There was an irony in this situation that would define my future direction of research from Triassic to Cretaceous tetrapods. Studying the Indian dinosaur fossils collected by Barnum Brown during his historical honeymoon trip to Jabalpur, five decades earlier, forced me back home to India many times for extensive research and exploration.

Huene and Matley (1933) identified two large theropods, called carnosaurs at that time, from the Lameta Formation on the basis of skull architecture: *Indosuchus* and *Indosaurus*. I have identified the well-preserved jaw material of the Lameta theropod collected by Barnum Brown, as *Indosuchus* (Chatterjee 1978b). Later, these Lameta theropods were correctly identified as abelisaurs within Neotheropoda, a primitive well-known theropod clade that thrived during the Cretaceous Period in Argentina, Madagascar, and other Gondwana continents (Chatterjee and Rudra 1996). Like most theropods, abelisaurs were predatory bipeds, superficially resembling tyrannosaurs in size and proportion,

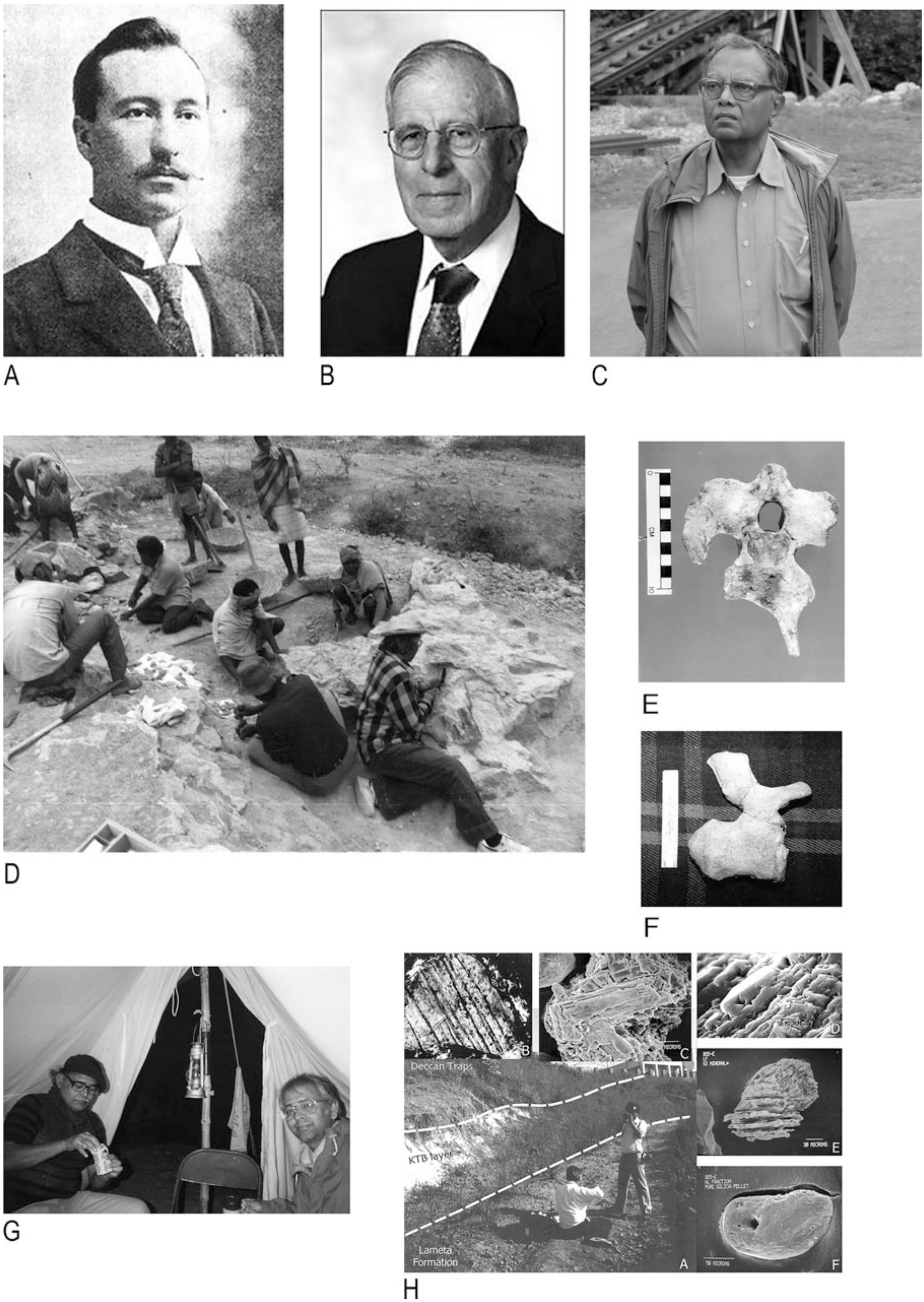


Fig. 8.16 Field photographs in the Late Cretaceous Lameta Formation at Bara Simla Hill, Jabalpur. **A**, Barnum Brown of the American Museum of Natural History, who discovered some dinosaur remains from the site in 1921, but later described by Sankar Chatterjee in 1978; **B**, Joseph Gregory, chairman of the Paleontology department at the University of California, Berkeley, who invited Sankar Chatterjee at his department; **C**, Dhiraj Rudra, then head of the Geology unit of Indian Statistical Institute, who accompanied Sankar Chatterjee in the field; **D**, excavation of a titanosaurid *Jainosaurus* at Bara Simla Hill; **E** and **F**, braincase and caudal vertebra of *Jainosaurus*; **G**, Pranab Majumdar and Sankar Chatterjee in front of the camp; **H**, Cretaceous-Paleogene Boundary ejecta layer at Bara Simla Hill, showing evidence of shocked quartz grains in thin section and SEM photographs from this layer (after Chatterjee t al. 2006)

though phylogenetically more primitive. They had stocky hindlimbs and extensive ornamentation in the skull bones.

Another surprise was waiting for me in the USA. While looking at the Barnum Brown collection at AMNH in New York, I discovered an osteoderm of a titanosaur from the Jabalpur site, which was later described by us (D'Emic et al. 2009). My research on the Late Cretaceous Lameta dinosaur material at America would inspire me to visit the Jabalpur site, collect additional dinosaur material from other sites of the Lameta Formation, and study the Deccan volcanism, Shiva crater, and Cretaceous-Paleogene Boundary (K-Pg) mass extinction. If I had never been invited to Berkley I never would have arrived at my current research on Cretaceous dinosaurs, and their extinction.

A Passage to India: Discovery of Cretaceous Dinosaurs

I spent several field seasons in India in collaboration with Dhiraj Rudra, then Head of the Geology unit of the Indian Statistical Institute, to collect the last evolutionary taxa of dinosaurs of India, and study the causes and consequences of their extinction at K-Pg boundary. My wife Sibani accompanied me on several field trips in India. We visited different Lameta sites in Madhya Pradesh and Gujarat and the Kallamedu site in the Cauvery Basin of Tamil Nadu in search of the Maastrichtian dinosaurs. The most productive fossil localities in the Lameta Formation are located near Rahioli village in Balasinor, Jabalpur, and Pisdura regions, traversing a linear E-W stretch of approximately 700 km. During our field work, we discovered remarkable remains of dinosaurs and their eggs in Balasinor and Jabalpur, identified the Shiva crater at the western shelf of India (which is linked to dinosaur extinction), and collected K-Pg boundary samples for meteoritic impacts (Chatterjee and Rudra 1996; Chatterjee et al. 2006; Novas et al. 2010). All these expeditions to India were funded by the National Geographic Society and Smithsonian Institution, and the field logistics were provided by the Indian Statistical Institute. The new dinosaur material from these expeditions is housed at the Geology Museum of Indian Statistical Institute.

The Lameta Dinosaurs

During my field work in the Lameta Formation in 1987–88, my first task was to locate the classical dinosaur fossil site on the western slope of Bara Simla Hill of Jabalpur where Matley, Sleeman, and Brown collected the material. Because of vegetation and monsoon rains, the Bara Simla site remained lost for almost 60 years. It was frequently visited by geology students for field work, their professors proudly reminding them this was where the very first dinosaur was discovered; but nobody knew from exactly what horizon of the Bara Simla Hill the dinosaur fossils had been collected. Dhiraj Rudra (Fig. 8.16C) and Pranab Majumdar (Fig. 8.16G) from ISI, and my wife Sibani assisted me in my search for the original dig. One day, after a futile week- long search, Sibani sat on a rock for our midday lunch break. I suddenly realized that was no rock my wife was sitting on, it was in fact a sauropod femur! The site matched perfectly with Captain Sleeman's 1928 description of the bone bed close to his bungalow, where he found fossil fragments of animals and plants in the sediments below the Deccan Trap.

For many years the dinosaur site was a restricted military area; as a Captain, Sleeman had no problem gaining access, we however had to get formal permission from Colonel A. M. Kapoor of the Gun and Shell Factory to dig. Over the next two weeks, under his military protection, we uncovered the site: first exposing Sibani's lunch-break femur, then some vertebrae, ribs, and a beautiful braincase all belonging to a titanosaur *Jainosaurus* (Chatterjee and Rudra 1996) (Fig. 8.16D, E, F). Our discovery made big headlines in the local newspaper and TV channel, inspiring the local school children and college students to visit the site. To control the crowd and protect the site, Colonel Kapoor posted a soldier as sentry with a rifle. It was quite hilarious to see an armed soldier guarding 65-million-year-old dinosaur bones as a national treasure. On that trip, on the opposite Chota Simla hill, we also discovered a titanosaur nesting site, near the Shiva temple. Here, Matley had collected an associated partial skeleton of a titanosaur *Jainosaurus* during 1932–33, which was sent to the British Museum of Natural History, and described by Wilson et al. (2011).

In the Bara Simla site, above the dinosaur-bearing bed, a 2.7 m- thick sandstone layer has yielded shocked quartz grains in the upper part of a sandstone layer, indicating the close proximity of a crater in India (which was later identified as the Shiva crater) from which thick ejecta could be emplaced ballistically. Shocked quartz grains from the Jabalpur section are coarse, and larger (300–400 μm) than most of the shocked quartz grains reported elsewhere, implying that the proximity of the crater was close by. Such coarse-grained and a thick boundary layer could not be derived as airborne fallout from the Chicxulub impact crater (Chatterjee et al. 2006). In this single site we see both the very last dinosaurs, and the cause of their extinction in the form of Shiva ejecta layer covering the bone bed.

The Lameta Formation has yielded two major groups of Gondwana dinosaurs—titanosaurid sauropods and abelisaurid theropods (Fig. 8.17), as well as a solitary ankylosaur (Huene and Matley1933, Chatterjee and Rudra 1996, Wilson et al. 2005, Novas et al. 2010, Chatterjee et al. 2017). Many of the original dinosaur taxa that were erected by early English paleontologists were based on fragmentary or

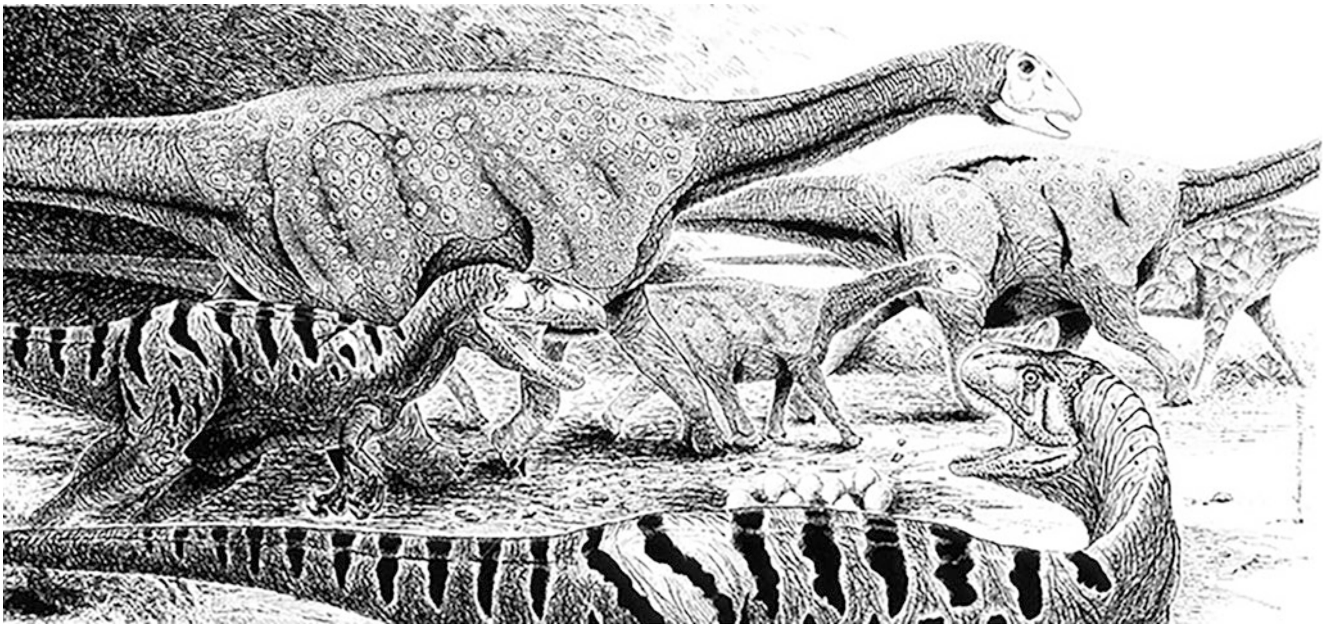


Fig. 8.17 Interaction of Late Cretaceous (Maastrichtian) Lameta dinosaurs. In the foreground two individuals of abelisaurid theropod *Rahiolisaurus* are aggressively looking for the opportunity to attack the young or weak individuals among the herd of armored titanosaur *Jainosaurus* at their nesting site. Large adult titanosaurs shielded their young at the center (after Chatterjee and Rudra 1996)

isolated material and their utility for phylogeny and paleobiogeographic analysis has since proven questionable. Recent discoveries of extensive dinosaur material from the Bara Simla quarry of Jabalpur and Rahioli quarry of Gujarat, as well titanosaurid eggs, have provided a more accurate understanding (Chatterjee and Rudra 1996, Novas et al. 2010). This dinosaur material, now housed at the Geology Museum of the Indian Statistical Institute, provides half of the story. The other half derives from the discovery of widespread dinosaur nesting sites from several infratrappean localities in Jabalpur, Kheda, Balasinor, Rahioli, Dohad, and Bagh in the Narmada Valley. These represent one of the most geographically extensive nesting sites known in the world (Prasad and Sahni 2014).

Titanosaurs

Titanosaurs were the most diverse and geographically widespread clade of Cretaceous sauropods in Gondwana, and have been recorded from all of the southern continents including Antarctica. From South America, titanosaurs also migrated to North America during the Late Cretaceous Period through the isthmus of Panama, and are represented by *Alamaosaurus* in the Big Bend National Park of Texas. Titanosaurs were the largest terrestrial animals in Gondwana and the only sauropod that possessed osteoderms. They are regarded as the most advanced of all sauropods, stockier and more robustly built. To date, 40 titanosaurian genera have been discovered all over the world, but the greatest numbers come from Patagonia in Argentina. Fossil evidence provides remarkable anatomical details about osteology, skin impressions, body armor, embryos, eggs, nests, and footprints (Novas 2009).

In India, fragmentary titanosaur remains were discovered from multiple localities in the Lameta Formation (Lydekker 1877, Matley 1923, Huene and Matley 1933). During 1984–1986, my colleague at ISI, Sohan Lal Jain collected a braincase and associated and mostly articulated postcranial material of a titanosaur from the fluvio-lacustrine deposit of the Lameta Formation in the Dongargaon locality of Chandrapur district, Maharasthtra, about 16 km south-east from the well-known Pisdura locality. Bones were concentrated in an excavated site of 184 m^2 area, and the association strongly suggested the presence of a single individual. The braincase from this collection was described by Berman and Jain (1982). Several large sauropod eggs and coprolites have also been known from this locality. Later, Jain and Bandopadhyaya (1997) described the postcranial material as *Titanosaurus colberti*, honoring E. H. Colbert of AMNH, who visited ISI in 1964 and 1977 to see the progress of *Barapasaurus* material and inspire paleontologists. Wilson and Upchurch (2003) replaced the generic name *Titanosaurus* with the new name *Isisaurus*, honoring ISI, because it possessed some unique characters. *Isisaurus colberti* had a short, vertically directed neck and long forelimb, making it considerably different from other sauropods. Cervicals and dorsals are opisthocoelous with well-marked pleurocoels;

caudals are procoelous throughout the series. *Isisaurus* is known from much better remains than most titanosaurs.

With the recent discovery of new cranial and postcranial material, Indian titanosaurs can be grouped into two distinct taxa: *Jainosaurus septentrionalis* (Chatterjee and Rudra 1996, Wilson et al. 2005, 2011) and *Isisaurus colberti* (Jain and Bandyopadhyay 1997). Although *Jainosaurus* and *Isisaurus* coexisted in India, the braincase morphology of these two genera is remarkably different, indicating they were not closely related to each other (Fig. 8.18). Both genera are sympatric and relatively large (~25 m). Our field collection of titanosaur braincase material suggests that *Jainosaurus* remains are dominant in the Bara Simla Hill, but *Isisaurus* material is prevalent in both Dongargaon and Rahioli sites.

There are about 10 species of titanosaurs that possessed osteoderms, which are reported from Brazil, Argentina, Mali, Malawi, Madagascar, India, and Spain. A large ellipsoid osteoderm of a titanosaur from the Bara Simla Hill of Jabalpur, collected by Barnum Brown, is associated with *Jainosaurus* material (D'Emic et al. 2009). *Jainosaurus* appears to be the most basal member of titanosaurs and shows close affinities with other titanosaurs such as *Malawisaurus* of Africa, and *Mendozasaurus* of South America, characterized by the development of scutes. The braincase of *Jainosaurus* resembles that of *Vahiny* from the Late Cretaceous of Madagascar indicating their closely phyletic relationships (Rogers and Wilson 2014). *Jainosaurus* is grouped in the Titanosauridae (Novas 2009).

The osteoderm appears to be absent in associated skeletons of *Isisaurus*, indicating that the taxon was not armored. *Isisaurus*, which appears to be more derived than *Jainosaurus*, has been reported from the contemporary Pab Formation of Pakistan on the basis of a braincase (Wilson et al. 2005). *Isisaurus* shows similarities to *Antarctosaurus* and *Argentinosaurus* of Argentina, *Opisthocoelicoda* of Mongolia, and *Alamosaurus* of North America; these taxa are accommodated in the family Antarctosauridae. In India, the oldest titanosaurian remains may come from the Nimar Sandstone (Cenomian-Turonian) in Narmada Valley (Khosla et al. 2003), or even earlier from the Late Jurassic Bagra Formation (Chatterjee and Hotton 1986). The distribution of titanosaur body fossils is complemented by their abundant footprint record, which hints at a much earlier origin, in the early or Middle Jurassic (Wilson and Upchurch 2005).

The presence of titanosaur osteoderm in India extends the geographic range of armored titanosaurs to India, Africa, Madagascar, South America, and Europe. Titanosaurids were widespread, known from the Late Cretaceous deposits of South America, Australia, North America, Mongolia, and China. Although titanosaurids were dominantly Gondwanan sauropods, they migrated from South America to North America, and to Eurasia via India.

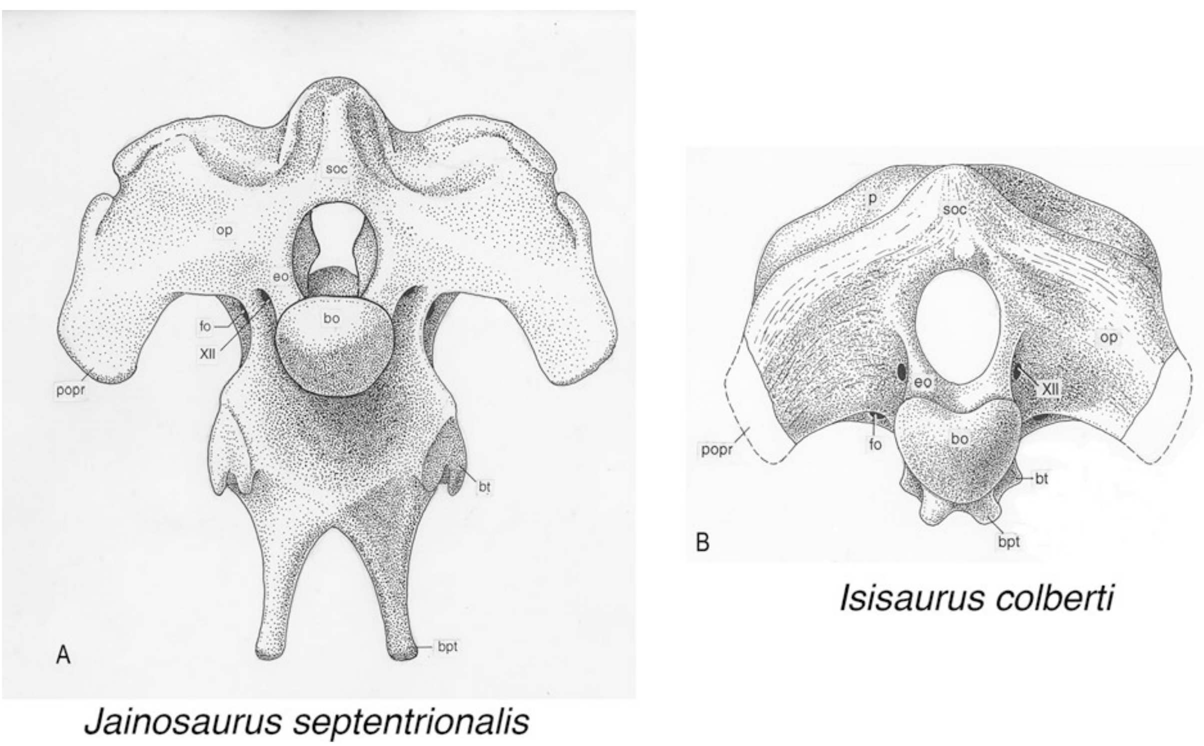


Fig. 8.18 Titanosaurid braincase. **A**, *Jainosaurus* from Jabalpur site; **B**, *Isisaurus* from Rahioli site. The braincase morphology of two taxa is remarkably different, suggesting their different phylogenetic positions in titanosaurid cladogram

Abelisaurs

Like titanosaurs, abelisaurs were distinctive Gondwanan dinosaurs. They were large predatory dinosaurs with a disjunct distribution across the Gondwana landmass during the Cretaceous, and have been recorded from South America, India, Madagascar, and Africa. They are derived members of the ceratosaurian clade, which originated in the Jurassic of Laurasia, but diversified in the Cretaceous of Gondwana. Like other theropods, they were fully bipedal and had forelimbs that were greatly reduced. Diagnostic characters of abelisaurids include anteroposteriorly short and deep premaxialla; dorsoventrally deep snouts at the level of narial openings; frontals dorsoventrally thickened resulting in a dorsal buckling (*Abelisaurus* of Argentina), paired horn-like structures (*Carnotosaurus* of Argentina), or a dome-like prominence (*Majungasaurus* of Madagascar) (Novas 2009). Abelisaurs contain two distinct families: the small and primitive Noasauridae, and the large and more derived Abelisauridae, which were the Gondwanan version of *T. rex*, though highly primitive. Both noasaurids and abelisaurids are known from the Lameta Formation. Novas et al. (2004) reviewed the abelisaurid material from the Lameta Formation originally described by Huene and Matley (1933). They identified *Laevisuchus indicus* as a small noasaurid, related to *Noasaurus* of Argentina and *Masiakasaurus* of Madagascar on the basis of their peculiar cervical vertebrae.

Indosuchus and *Indosaurus* were diagnosed on the basis of isolated cranial elements (Chatterjee 1978b). The skull roof of both genera is smooth without any horn-like protuberance as is the condition of *Abelisaurus* of Argentina. However, the distinctive peg-and-socket articulation between the lacrimal and the frontal bone of *Indosuchus* is very similar to that of *Abelisaurus* (Novas et al. 2004).

In the early 1980s, Suresh Srivastava, a paleontologist from the Geological Survey of India, discovered some disarticulated skeletons of an abelisaurid dinosaur around Temple Hill, near Rahioli village in the Balasinor area of Gujarat. The material was later described by Wilson et al. (2003) as a new taxon, *Rajasaurus narmadensis*. We decided to explore Rahioli site for additional dinosaur material. During our field work in 1995, we discovered a rich graveyard of multispecies, a dinosaur bone bed in the mudstone facies of the Lameta Formation showing disarticulated elements of titanosaurid, abelisaurid, and nodosaurid remains (Fig. 8.19). In this trip, Dhiraj Rudra from ISI and my wife and two sons participated in the excavation. The most remarkable discovery from this quarry represents a nearly complete postcranial skeleton of a large abelisaurid theropod *Rahiolisaurus* (the genus is named after the Rahioli village; Novas et al. 2010) (Fig. 8.19A). In addition, the quarry has yielded bones of a small abelisaur, probably a noasaurid, limbs and girdles of a titanosaur *Isisaurus* associated with a braincase (Fig. 8.19B, C), and several bones of a nodosaurid ankylosaur (Fig. 8.19E, F). Also, we recovered intact titanosaurid eggs in and around this area (Fig. 8.19D). Later, this site was designated as the 'Dinosaur Fossil Park' by the Geological Survey of India and has become a tourist location in Gujarat.

It is likely that *Indosuchus*, *Indosaurus*, and *Rahiolisaurus* may represent the basal members of abelisaurids, similar to *Abelisaurus* of Argentina. From the associated postcranial material, it appears that *Rahiolisaurus* was a gracile and slender-limbed, basal abelisaurid, whereas *Rajasaurus* was a heavy-bodied, stout-limbed form. An adult-sized *Rahiolisaurus* was identified as a large-sized abelisaurid, about 8 m long (Novas et al. 2010). *Rahiolisaurus* had seven co-ossified sacral vertebrae and is more derived than *Majungasaurus* of Madagascar but resembles *Carnotaurus* of Argentina in many postcranial features and shares a close ancestry. The lack of a skull roof precludes conclusions on whether or not *Rahiolisaurus* was a derived member of the horned abelisaurid clade Carnotaurinae.

Rajasaurus, another abelisaur from this site, is known from associated skull and postcranial elements (Wilson et al. 2003). The pelvic and hindlimb elements of *Lametasaurus* were included with *Rajasaurus* because of close morphological similarity. However, the partial skull roof and head crest of *Rajasaurus* is very distinctive and more derived than other Lameta abelisaurs. The skull roof of *Rajasaurus* shows a single frontal horn (Wilson et al. 2003) like that of *Majungasaurus* of Madagascar, whereas *Carnotaurus* of Argentina had developed a pair of bull-like horns. In life, these horns were probably encased in keratin sheath. These horned abelisaurs – *Rajasaurus*, *Majungasaurus* and *Carnotaurus* – are grouped in a highly derived subfamily Carnotaurinae of abelisaurids (Novas 2009). It thus appears that *Rajasaurus* is the most derived member of Indian abelisaurs.

The distribution of closely related abelisaur taxa indicates that dispersal routes between India-Madagascar and India-South America were operative during the Late Cretaceous period via Antarctica-90º East Ridge (Fig. 8.15C). The recent discovery of abelosauroid antecedents from the Early Cretaceous, noasaurids and abelisaurids from the Mid-Cretaceous, and a hornless abelisaurid from early Late Cretaceous of Niger provides evidence for the origin of this group on Africa, thus indicating 'Pan-Gondwana' distribution (Sereno et al. 2004). However, a record of an early abelisaur from Europe indicates more widespread distribution between Laurasia and Gondwana. Tortosa et al. (2014) reported a new abelisaur *Acrovenator* from the late Cretaceous deposits of southern France. Phylogenetically, *Acrovenator* is extremely similar to Indian taxa such as *Rajasaurus*, *Rahiolisaurus*, *Indosaurus* as well as the Madagascan genus *Majungasaurus*, and all grouped in a

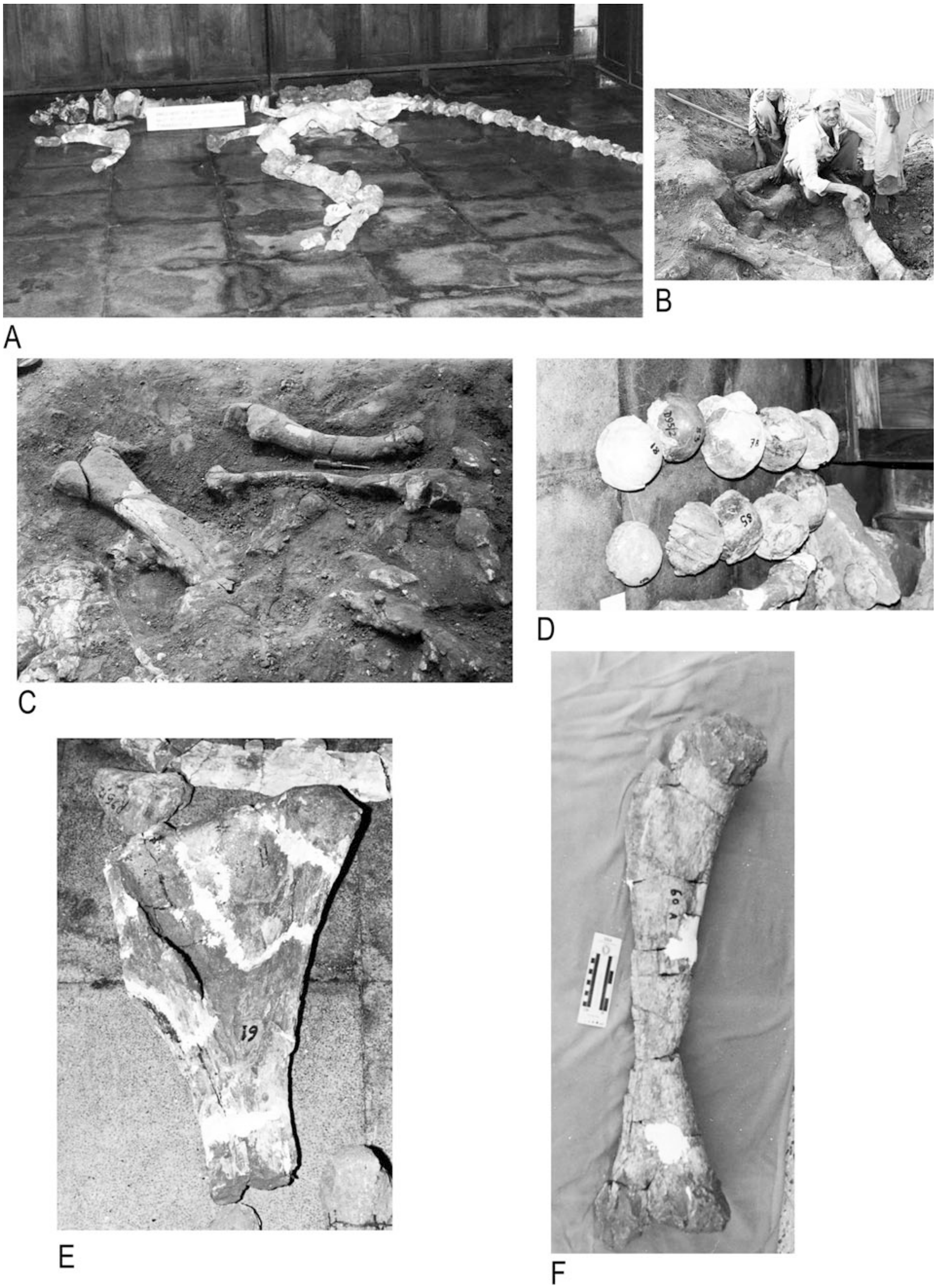


Fig. 8.19 Field photographs of the Late Cretaceous Lameta Formation in Rahioli site. **A**, a nearly complete skeleton of an abelisaurid theropod *Rahiolisaurus*; **B**, excavation of titanosaurid bones; **C**, disarticulated elements of titanosaurid and abelisaurid; **D**, titanosaurid spherical eggs; **E**, proximal end of an ankylosaur humerus; **F**, femur of an ankylosaur

new subfamily Majungsaurinae. Since *Acrovenator* is Late Campanian in age, whereas Indo-Madagascaran abelisaurids are Maastrichtian, it is most likely that post-Cenomanian interchanges occurred among Europe, Africa, India, and Madagascar. Dispersal routes between India and Africa via the OKL Arc, and between India and Madagascar via the Laxmi Ridge-Seychelles remained effective during the Late Cretaceous. To date, no records of abelisaurs have been reported in Antarctica and Australia.

Ankylosaurs

The ankylosaur is a quadrupedal herbivorous group of armored dinosaurs known largely from the Late Cretaceous deposits of all continents with the possible exception of Africa, ranging from the Kimmeridgian to the end of the Maastrichtian. The solitary ornithischian misidentified from the Lameta Formation is *Lametasaurus*, was classified as a stegosaur on the basis of a number of dermal scutes, sacrum containing 5 sacral vertebrae, a pelvis, a tibia, and teeth (Matley 1923). However, *Lametasaurus* is a fossil chimera; most skeletal elements in the original description, especially the hindlimbs and pelvis have been allocated to *Rajasaurus* (Wilson et al. 2003) and are now regarded as a *nomen dubium* (Novas et al. 2010). In 1995, we discovered associated material of an ankylosaur from the Lameta Formation near Rahioli quarry, possibly a nodosaurid, represented by several spines, limbs and girdle bones, indicating its presence in India during the Maastrichtian time (Chatterjee and Rudra 1996). The new material represents isolated vertebrae, scapulocoracoid, humerus, femur, and several pieces of armor such as hollow lateral spikes and solid dorsal scutes typical of ankylosaurs (Fig. 8.19E, F).

Although most ankylosaurs are known from Laurasian landmasses, in recent times, some Gondwana ankylosaurs have been discovered. However, Gondwana dinosaurs were less abundant and less derived than the Laurasian taxa. For example, the recorded ankylosaurs from Gondwana belongs to Nodosauridae; no members of more-derived Ankylosauridae have been discovered in the southern landmasses. For example, *Minmi* from the Early Cretaceous of Australia is a small, basal ankylosaur that might have radiated to other Gondwana landmasses (Molnar 1980). Coria and Saladago (2001) reported the presence of a nodosaurid from the Late Cretaceous Allen Formation of Patagonia. *Antarctopedia* is another basal nodosaurid ankylosaur from the Late Cretaceous of Antarctica (Saladago and Gasparini 2006). The presence of a new nodosaurid from the Lameta Formation indicates that the clade was widespread on the Gondwana landmasses during the Cretaceous.

Kallamedu Formation

During 1998, we explored the Late Cretaceous Kallamedu Formation of Ariyalur in Tamil Nadu in search of the last dinosaurs. We found isolated elements of titanosaurs, theropod teeth, crocodiles, birds, and a beautiful skeleton of a side necked turtle *Kurmademys* (Gaffeny et al. 2001). Here in a stream section, we discovered a 2m-thick, marine oyster-rich, coarse-grained tsunami deposit overlying the continental dinosaur-bearing Kallamedu Formation at the K-Pg boundary. We interpreted the tsunami deposit, linking it to the Shiva impact event (Chatterjee et al. 2006).

Goswami et al. (2013) reported an isolated troodontid tooth serrated with typical coarse-denticles from the Kallamedu Formation of Cauvery Basin, Tamil Nadu. Troodontid is a small-bodied, maniraptoran theropod, predominantly restricted to North America, Europe, and Asia. Discovery of a troodontid from India indicates faunal migration from Laurasia to India via the OKL Arc during the Late Cretaceous time. Abelisaurid teeth and a simosuchid crocodile tooth have also been described from this site indicating faunal exchanges between India and Madagascar during the Late Cretaceous (Prasad et al. 2013).

Dinosaur Eggs and Babies

A fairly extensive record of large, spherical titanosaurid egg clutches, eggshell fragments, and nesting sites have been found in the Lameta Formation can be traced almost continuously along the north of the Narmada Rift from Jabalpur in Madhya Pradesh to Anjar in Gujarat, running over 1,000 km in E-W direction. Both complete and fragmented, these eggs and eggshells are restricted to a thin (3–12 m) lithological unit, a calcareous sandstone of the Lameta Formation, which is interpreted as calcretized paleosol (Sahni and Khosla 1994). These dinosaur nesting sites, comprised of hundreds of nests and thousands of eggs, represent the largest dinosaur hatchery in the world from a single lithological unit (Sahni et al. 1994). Most of these eggs belong to titanosaurids (Fig. 8.19D). These egg-bearing horizons were laid down intermittently across a wide river flood plain during a period when the climate varied between semi-arid and subhumid conditions. The spectacular eruptions of Deccan volcanism began during that time, covering much of central and western India, destroying the habitats of dinosaurs.

Most titanosaurid egg clutches contain about 10 to 12 spherical eggs ranging in diameter from 15 to 20 cm, and were laid down in excavated hollows in linear and circular

fashion. The density of clutches suggests that on each occasion, a large number of gregarious females laid eggs at the same time and in the same nesting ground. The sheer size of the adults and proximity of the clutches suggest little or no parental care took place once the eggs were laid – there simply would not have been room for all the parents to tend their young at the same time. The eggs were presumably laid down by two known titanosaurid genera – *Isisaurus* (Pisdura and Balasinor areas) and *Jainosaurus* (Jabalpur area).

The microstructure of the fossil egg shell provides some clue to the producer of the egg. As a rule, large eggs have thick shells and small eggs have thin shells. All these eggs have been grouped under the oogenera *Megaloolithus* Mikhailov 1991 and *Fusioolithus* Fernández and Khosla 2015 and have nine distinct morphostructural units (Khosla and Sahni 1995, Vianey-Liaud et al. 2003). The eggshell is largely made of polycrystalline calcite minerals held in a matrix of collagen fibers. The microscopic structure of the shell in cross section reveals two main layers—an inner mammillary layer and an outer spongy, or palisade layer. The spongy layer is thicker, with calcite crystals arranged in the protein matrix as vertical palisades, separated by minute pore canals. The microscopic structure of the shell in cross section reveals a variation in number of layers among dinosaurs: a single layer is found in sauropods and ornthischians, two distinct layers in theropods, and three layers in birds. Pore canals pass through the shell to permit embryonic gas exchange (Chatterjee 2015). The cross-section of a typical titanosaurid eggshell from the Lameta Formation shows the development of a single layer (basal mammillary layer), separated by pore canals penetrating the thickness of the eggshell, which may vary about 2 to 4 mm in diameter (Sahni et al. 1994). Similar titanosaurid eggs are known from France, Spain, and Patagonia.

Baby dinosaurs have long been a source of fascination to both paleontologists and public. Unlike other dinosaur nesting sites such as Montana, Alberta, Gobi Desert, China, and Argentina, where embryos, hatchlings, and juveniles are common in the nests, no such skeletal remains of baby dinosaurs have yet been recovered from India (except one example) despite such extensive nesting sites. The absence of dinosaur hatchlings and juveniles in India is very unusual and intriguing. Hatchling failure is common in birds, often linked to environmental contamination by pesticides and waste disposal. Perhaps pollution from the Deccan volcanic emission might have contributed largely to the hatchling failure of Indian dinosaurs.

Unlike some dinosaurs, the giant titanosaurids did not care for their eggs. Adults have never been found near nests, so it seems that sauropod hatchlings had to fend themselves from the start, as suggested by their precocial development of the skeleton. And that left the way clear for predators to feast on them as they emerged. There may be one rare example - a partial skeleton of a titanosaurid hatchling, collected from the Dholi-Dungri village, near Balasinor of Gujarat. It is represented by a portion of the left side of the anterior thorax, a partial shoulder girdle and forelimb preserved in anatomical articulation, and the bones are completely ossified (Wilson et al. 2010). An articulated skeleton of a snake *Sanajeh* was found coiled around an egg in a nesting site; the skeleton of a titanosaur hatchling lay nearby (Fig. 8.20). This suggests that *Sanajeh* was a predator caught in the act of devouring a hatchling. Like many early snakes, *Sanajeh* did not have the wide gape seen in boids and pythons and it would have been difficult to crack or swallow titanosaur eggs, which were large, spherical ($\sim$14–20 cm diameter), and thick-shelled. Most likely, it was an opportunistic hunter, preying on babies. Titanosaurs in the Lameta ecology such as *Isisaurus* and *Jainosaurus* were large (20–25 m), and were effective deterrents to predators, but their small hatchlings (50 cm), unguarded by parents, were easy prey for stealthy predators like snakes.

Dinosaur Coprolites and Food Preference

The adaptive radiation of dinosaurs resulted in the evolution of a host of species in both the herbivore and carnivore guilds. Identifying the food habits of many dinosaurs are fairly straightforward from their tooth morphology, tooth wear facets, inferred jaw mechanics, as well as general body plan. Sauropods and ornithischians were herbivores, but theropods were carnivores. Coprolite composition can discriminate between herbivores and carnivores. Plant dietary residues are common in coprolites produced by herbivores. On the other hand, inclusions of bone fragments, teeth, fish scales, or mollusk shells provide evidence of carnivory. Additionally, isotopic geochemistry of the preserved stomach contents of some fossils, and coprolites, and the depositional environment in which dinosaurs are found, in association with local plant fossils, can help us to infer their preferred diets.

One of the most novel discoveries was found in the titanosaur diet - phytolith fossils (silicified grasses) were found in titanosaur coprolites from Pisdura, central India. Dinosaur coprolites are rarely preserved in exceptionally favorably conditions because feces are largely composed of soft material. They have been recognized by their familiar fecal shapes, but are highly variable. Matley (1933) discovered a large number of coprolites from the Lameta Formation of Pisdura locality attributed to titanosaur (*Isisaurus*), whose bones were found in the same locality. The large elongated droppings are up to 10 cm wide and 17 cm long, cylindrical, and certainly indicate hefty plant source material. A variety of coprolitic segments have yielded woody

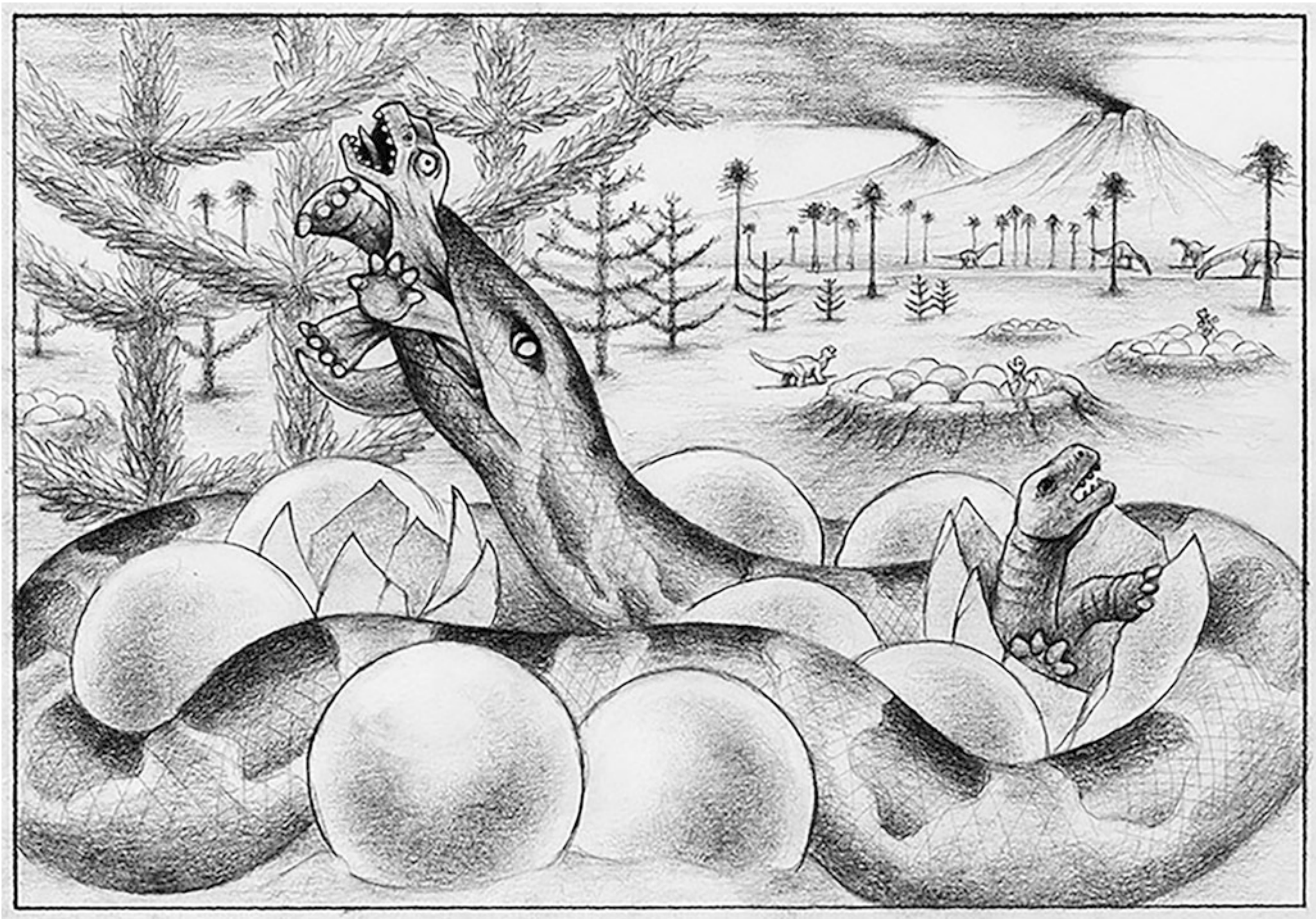


Fig. 8.20 Active nesting sites of the Late Cretaceous Lameta titanosaurs in Rahioli, Gujarat. Life restoration of a large madtsoiid snake *Sanajeh* devouring a newly hatched titanosaur (*Rahiolisaurus*) as the adults are at the distant river. At the background Deccan volcano is erupting (after Chatterjee et al. 2017)

tissue, cuticles, pollen, and water-ingested microorganisms. The plant tissues are mostly of gymnosperm origin. Carbon isotopic ratio ($^{13}C/^{12}C$) and other markers from the coprolites suggest that titanosaurs used C_3 vegetation as its primary diet. On the other hand, gut fermentation may not have been an active mechanism in the digestion process of titanosaurs (Ghosh et al. 2003). Prasad et al. (2005) documented that the grass fossils, in the form of phytoliths, are preserved in the Pisdura coprolites. They concluded that titanosaurs fed indiscriminately on a wide range of C_3 plants including dicotyledons, conifers, palms as well as five taxa of extant grasses (Poaceae).

About one-third of the Earth's vegetative cover comprises savannas, grasslands, and other grass-dominated ecosystems, but the early history of grass is obscure. It is generally believed that dinosaurs did not eat grasses, because the earliest fossil record comes from the Paleocene sediments. The phytoliths from the Pisdura coprolites shed new light on the early origin of grass and suggest that grass covered the Late Cretaceous ecosystem as a green blanket and provided food for herbivorous dinosaurs.

Night: Death of the Dinosaurs

At the Cretaceous-Paleogene (K-Pg) boundary, the Indian plate had moved considerably northward with the subduction of the Kshiroda Plate under Asia, gliding smoothly along two parallel transform faults on its two sides: the Owen-Chaman Fault in the west, and the Wharton Ridge-Sagaing Fault in the east (Fig. 8.21). In this paleobiogeographic setting, India was ground zero for two catastrophes, the Shiva impact and Deccan volcanism that heralded a biotic holocaust across the globe (Chatterjee et al. 2017).

The Cretaceous-Paleogene (K-Pg) boundary mass extinction ($\sim$66 Ma) is one of the most devastating events in the history of life, marking the end of the dinosaur era. The fossil record suggests that about 75% of the plant and animal species inhabiting the Earth perished at the end of the Cretaceous; this occurred over a geologically short period of time. In contrast to the end-Triassic extinction that gave the dinosaurs the advantage to diversify in the Jurassic, the

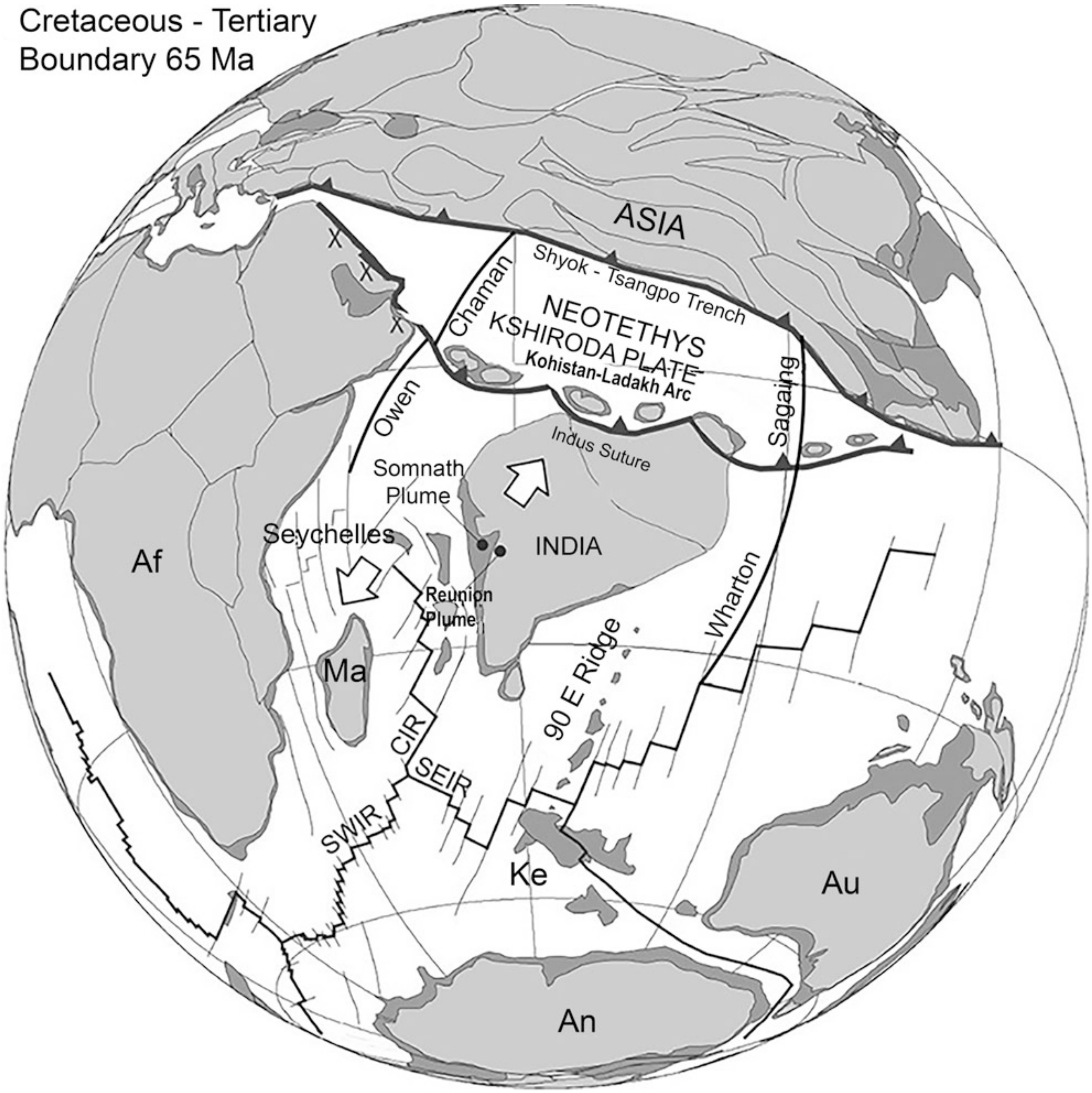


Fig. 8.21 Paleogeographic reconstruction of India in relation to other Gondwana continents during the Cretaceous-Tertiary boundary (~65 Ma). The Oman-Kohistan-Ladakh Arc maintained the biotic link between India and Africa (modified from Chatterjee et al. 2017)

end-Cretaceous extinction finally snuffed out the nonavian dinosaurs, along with the pterosaurs in the sky and the plesiosaurs and mosasaurs in the seas. The extinction also destroyed certain groups of mammals, birds, lizards, insects, and plants on land. In the oceans, ammonites, reef-building rudists, and most species of coccolithosphores and planktonic foraminifera died out. The K-Pg extinction was severe, global, rapid, and selective, affecting biotas of all the major continents and oceans.

The wealth of data accumulated over the past two decades suggests that dinosaurs disappeared suddenly at the K-Pg mass extinction event 66 million years ago (Brusatte et al. 2014). Many hypotheses have been offered over the years to explain dinosaur extinction, but only a few have received serious consideration. The K-Pg extinction was a global event, so we should examine globally effective agents: geographic change, oceanographic change, climatic change, or extraterrestrial events that could cause the environmental

crisis. Fossil record of marine plankton and terrestrial plants suggests that, in the last million years or so of the Cretaceous, the warm global climate that prevailed through the period was cooling in fits and spurts: Earth experienced a catastrophic winter at the K-Pg boundary (Scotese 2015). Large amounts of sulfuric acid aerosols, emitted from the Deccan Trap, blocked the sunlight and caused environmental stresses and periodic rapid cooling of Earth. Difficulty in assigning a single cause to end-Cretaceous extinction rests on a series of events that nearly simultaneously occurred: massive volcanism such as the Deccan Traps and the extraterrestrial bolide impacts. The most recent work on the K-Pg extinction has centered on two hypotheses that suggest a violent end to the Cretaceous: twin large asteroid impacts, and a giant volcanic eruption such as Deccan Traps.

Asteroid Impacts

A key breakthrough in the dinosaur extinction debate occurred in 1980, when Alvarez at al. (1980) discovered high concentrations of an iridium anomaly from a 2.5 cm-thick clay layer at the K-Pg boundary marine sections of Gubbio Italy and Stevens Klint in Denmark. As iridium remains abundant in carbonaceous chondrites, the Alvarez team suggested that a giant asteroid, about 10 km in diameter, struck the earth at the time of K-Pg boundary and produced a circummundane dust cloud that blocked the Sun, chilled the planet, and killed the dinosaurs and other organisms. They proposed that the iridium had settled out of a global dust cloud kicked up by the impact of the asteroid. Later, the iridium anomaly has been recognized globally in both continental and marine K-Pg boundary sections. Alvarez group had calculated from the amount of iridium dispersed around the globe that the source crater measures 150 to 200 km in diameter. The impact theory was strengthened by three additional independent forms of evidence in the K-Pg sediments in different parts of the world: (1) shocked quartz, a distinctive signature of an impact event (Bohor et al. 1987); spherules representing droplets of impact melts (Smit 1999); and (3) carbon soot particles resulting from global fires (Wolbach et al. 1988).

Chicxulub Crater, Yucatan Peninsula, Mexico

Locating the K-Pg impact crater would provide the most corroborative evidence of all for the asteroid impact theory, but prior to 1990, no crater of the right age and size has been discovered. Finding a killer 66 million years after the crime was committed is no easy task. Eventually, the K-Pg impact ejecta such as spherules, iridium anomalies, and shocked quartz around the Gulf Coast led to the crime scene in the Chicxulub crater on the northern margin of the Yucatan Peninsula in Mexico. The Chicxulub crater is more than 180 km in diameter, which is buried by 1,100 m of carbonate strata—half on land and half on the sea floor, but the gravity anomaly maps clearly reveal its morphology (Hildebrand et al. 1995). The gravimetric signature of the crater showed a semicircular outline, opening up toward the north-west in a horse-shoe pattern. Recent drill core samples from the crater have confirmed the radiometric date of the impact precisely, coinciding with the K-Pg boundary around 66 million years ago. Moreover, shocked quartz grains, impact melt rocks and breccias recovered from the drill core samples support the impact origin of the crater.

The Chicxulub crater is a pristine, well-preserved peak-ring crater similar to the Schrödinger crater on the Moon, linked to the K-Pg mass extinction event (Kring 2017). The peak ring formed in a matter of minutes. Just after the impact, deep granite bedrock, flowing like a liquid, rebounded into a central tower as tall as 10 km before collapsing into a circular ridge. The sharp iridium peak and ejecta components such as glass spherules and shocked quartz at the thin K-Pg boundary sections in different parts of the globe suggest that the impact-induced catastrophes lasted for extremely short time periods—virtually a geological blink of an eye. The impact caused giant tsunamis in all directions. The emission of dust and particles caused environmental changes close to a nuclear winter. For the past. 30 years, many scientists have claimed the Chicxulub impact to be sole cause for the K-Pg mass extinction, though not without controversy. One of the strongest critics is Gerta Keller, who suggested that Chicxulub impact occurred about 100,000–150,000 years before the K-Pg mass extinction. She suggested that there were multiple impacts at the K-Pg transition (Keller 2014).

Shiva Crater, Mumbai Offshore Basin, India

Half a world away from Chicxulub, in what is now the Mumbai Offshore basin, a giant Shiva impact occurred at the K-Pg boundary, on the western shelf of India-Seychelles continent, which was drifting northward from the breakup of Gondwana (Fig. 8.21). A Ganymed-sized asteroid ($\sim$40 km diameter) striking the Mumbai offshore basin, excavated a large, multiringed complex crater ($\sim$500 km diameter), and extruded fluid ejecta along the downrange of the crater basin (Fig. 8.22A) (Chatterjee and Rudra 1996, Chatterjee et al. 2006, Chatterjee 2015). The Shiva crater (19°45′26″N, 71° 39′46″E) is largely submerged and buried by 2- to 4-km-thick strata of post-impact Tertiary sediments on the western shelf, but the eastern part of the crater rim, the

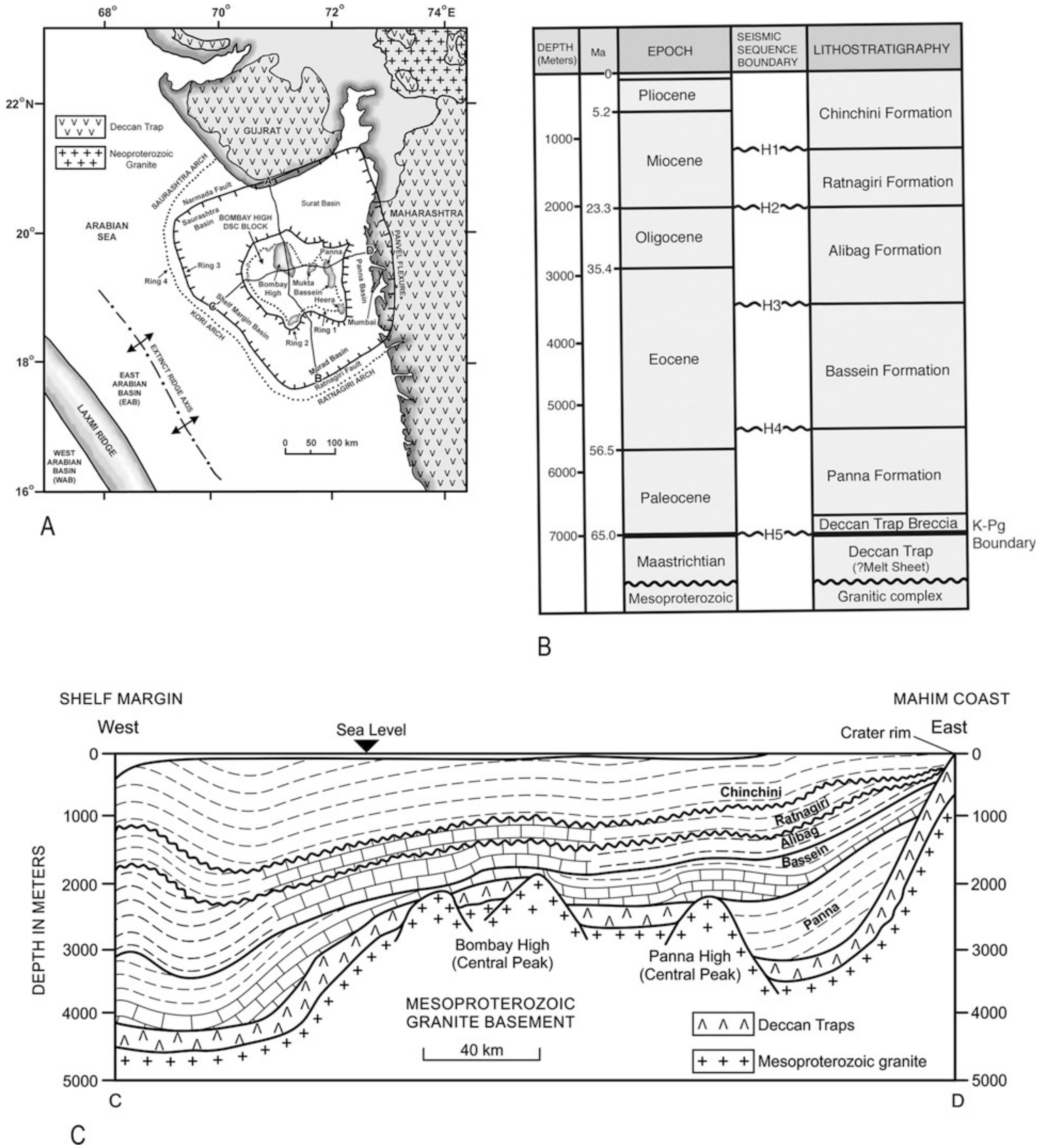


Fig. 8.22 Shiva crater on the western shelf of India. **A**, present day location of Shiva crater at the Mumbai offshore basin. The Shiva crater is a complex peak ring crater, about 500 km across and is buried by 4-km thick, post-impact sediments. The peak ring is about 200 km diameter and consists of several structural highs including Bombay High, Mukta High, Panna-Bassein High, Heera High and several unnamed peaks. The peak ring is the structural trap for oil and gas and is the largest oil field in India. **B**, generalized stratigraphy of the Shiva crater showing the target rocks at the basement, succeeded by the post-impact sediments. **C**, cross-section across the Shiva crater in west-east direction (C–D line in Fig. A), showing the peak rings, which are covered by post-impact sediments (modified from Chatterjee et al. 2006)

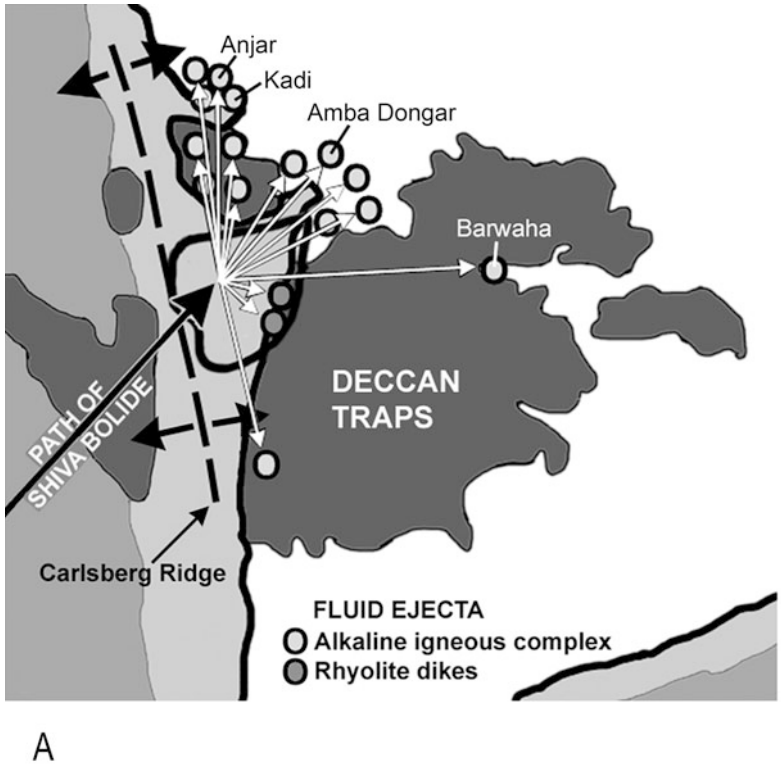
Panvel Flexure, comes onshore along the Mumbai coast and remains tectonically and geothermally active, resulting in hundreds of hot springs along this faulted margin (Fig. 8.22B, C). The central region of the crater lies in the Arabian Sea around Bombay High, the largest hydrocarbon field in India, which is located 160 km off the coast of Mumbai. The Oil and Natural Gas Corporation (ONGC) discovered and studied the basin in detail using geophysical

and deep drill core data, which are described in several scientific publications and internal reports (Rao and Talukdar 1980, Basu et al.1982, Bhandari and Jain 1984, Mathur and Nair 1993, Zutshi et al. 1993). The ONGC scientists have generously provided some of the drill core samples from the Bombay High and shared many unpublished data with me, which helped us to reconstruct the complex morphology of the subsurface structure of the Shiva crater and confirm its impact origin (Chatterjee et al. 2006).

The Shiva crater has been identified from gravity, seismic and well logs data and buried central peaks (Basu et al. 1982, Bhandari and Jain 1984, Mathur and Nair 1993, Rao and Talukdar 1980, Zutshi et al. 1993, Mehrotra et al. 2010). Gravity data of the Shiva crater show a significant gravity-low-anomaly over the central peaks of the Bombay High region, similar to the pattern of the Chicxulub crater (Hildebrand et al. 1995). Subsurface structure and stratigraphy of the Shiva crater are known primarily from petroleum exploration drill holes, and from seismic stratigraphy by the ONGC. The Shiva structure is a well-preserved, complex peak-ring crater with subsurface mountains, including Bombay High, Mukta High, Panna-Bassein High, Heera High, and several other unnamed peaks, which rise up to 4 km above the crater floor (Fig. 8.22A). The peak-ring consists of highly fractured Mesoproterozoic granite intruding through a veneer of the Deccan Trap, which was rebounded by the bolide impact. The granitic basement rocks of Bombay High field have yielded Rb-Sr isochron age of ~1450 Ma, which is interpreted as the formation and emplacement time of the granite during the Mesoproterozoic (Rathore et al. 2004). However, the radiometric clock of the basement rock was reset to a younger age by the Shiva impact event, but the precise date is not yet available. Most likely, the Proterozoic basement was the target rock for the impact. The peak-ring is about 250 km in diameter and is surrounded by annular trough, and is bordered outside by an elevated and faulted crater rim. The morphology of the Shiva crater closely approximates the Chicxulub Crater of Mexico and bears all the hallmarks of a large complex, peak-ring crater. However, the shape of the Shiva crater is more squarish than circular, like the Barringer crater of Arizona with a tear drop shape in the downrange direction because of the oblique impact. The post-impact sedimentation in the crater basin began with the Early Paleocene Panna Formation and continued through the Pliocene (Fig. 8.22B). These Tertiary strata are nearly horizontal, following the uneven surface of the crater floor. The sediments overlying the peak-ring form an ideal trap for petroleum accumulation and is the most productive oil horizon, where oil and gas is produced primarily from the Miocene reservoirs (Fig. 8.22 C). Exploration for hydrocarbons in the Bombay High field started in the early sixties, and the first oil discovery was made in the Miocene Limestone in 1974. Since then the basin is under active hydrocarbon exploration and exploitation. Ranked 38th worldwide, Shiva has reserves exceeding 4 billion barrels of oil, 24.2 trillion cubic feet of gas, and 0.3 barrels of natural gas liquid (Wandrey 2004). Many impact craters are the most productive hydrocarbon sites. Using K-Ar dating, Rathore et al. (1997) estimated the age of Deccan Trap basement rock around the K-Pg boundary (~66 Ma). The Deccan Trap and the overlying Paleocene Panna Formation together bracket the age of the Shiva crater right at the K-Pg boundary (Fig. 8.22B). Future radiometric dating of the drill core samples will provide additional evidence for the age of the crater.

We can speculate about the size and trajectory of the Shiva bolide. Using a scaling equation (Melosh 1989), the 500-km-diameter Shiva crater was formed by a bolide of 40 km in diameter, about the size of the 'Near Earth Asteroid' (NEA), Ganymed. The shape of the Shiva crater suggests the trajectory of the bolide. Although hypervelocity impacts normally create circular craters, impact from a low angle (~15º from the horizontal) generates an elongated teardrop crater such as the Messier and the Schiller craters on the Moon, Orcus Patera on the Mars, the Rio Cuarto crater in Argentina, and the Shiva crater in India. We speculate the Shiva bolide came from the southwest in a northeasterly direction at a low angle, where the tip of the teardrop indicates the downrange direction. The Shiva bolide flew obliquely from the southwest, over South Africa, and the Arabian Sea, before hitting the western shelf of India at roughly a 15° angle. It created a large oblique crater where it landed and showered India with a particular hard rain of fluid ejecta and dust. As a result, the ejecta was emplaced ballistically along the NE downrange direction. An oblique impact is more devastating than high-angle impact. The "dry target" rock consists of bilayered, rheologically variable Proterozoic granite and Deccan basalt (Chatterjee et al. 2006). The asymmetric distribution of fluid ejecta on the NE side of the Shiva crater indicates the downrange direction (Fig. 8.23A) (Chatterjee et al. 2006). The distribution of ejecta around the crater is more sensitive to the angle of impact and currently serves as the best guide to the obliquity of impacts.

The Shiva impact might have triggered the widespread distribution of the Deccan alkali volcanism that occurred during the late phase of Deccan eruption, because of the synchroneity of two events in space and time. Deccan alkali rocks have been reported from the basement of the Shiva crater (Rathore et al. 1997). Outside the crater, these spectacular volcanic plugs, which are arranged radially in Anjar, Kadi, Jwahar, Phenai Mata, Amba Dongar, Barwaha, Murud and Napsi, are dense with clearly defined zones of gravity-high, which are interpreted as the fluid ejecta of the Shiva impact in the downrange direction (Fig. 8.23A) (Chatterjee and Rudra 1996, Chatterjee et al. 2006). These



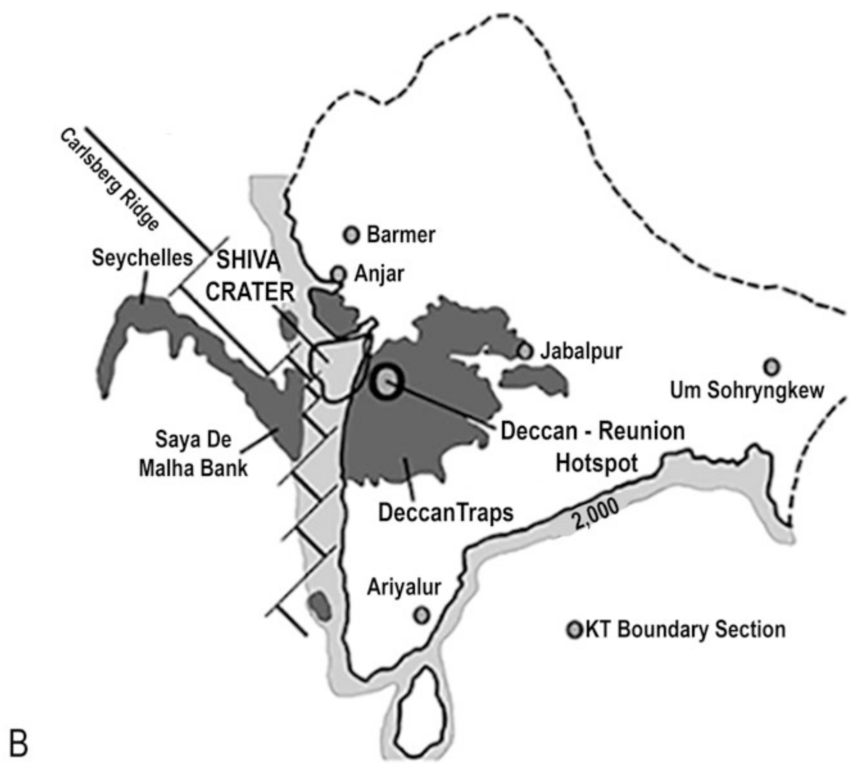


Fig. 8.23 **A**, radial, asymmetric distribution of fluid ejecta downrange of the Shiva crater; teardrop shape of the crater and asymmetric distribution of melt rocks indicate oblique impact along the NE downrange direction; **B**, Paleogeographic reconstruction showing the initial rift between India and Seychelles in the K-Pg boundary (~ 66 Ma). Both the Reunion plume and the Shiva impact have been linked to the separation of Seychelles from India (modified from Chatterjee et al. 2006);

impact melt rocks are rich in iridium, revealing their contamination from the impacting asteroid (Shukla et al. 2001) and showing their consistent ages around 66 Ma (Basu et al. 1993). Most likely, the Deccan alkali rocks represent the melt rocks of bilayered target rocks—Proterozoic granite and Deccan basalt—induced by the Shiva impact (Chatterjee et al. 2006). Drill core samples from the Shiva basin may unravel the origin of the Deccan alkali rocks. Similar lava-like fluid ejecta is common in lunar craters that were emplaced in a downrange to distances as great as a crater radius.

The shock metamorphism of rocks and mineral is an important consequence of hypervelocity impact events. The Proterozoic basement rock of the Shiva crater shows evidence of shock metamorphism, a crucial evidence of the bolide impact event. ONGC drill core samples of the Mesoproterozoic basement rock from the Bombay High show veins of pseudotachylite in the granite, which is usually attributed to bolide impact (Fig. 8.24A, B, C) (Chatterjee et al. 2006). Pseudotachylite is a dark, fine-grained rock that resembles volcanic glass. Both thin sections and SEM images confirm that the composition of the pseudotachylite is pure silica.

The common forms of titanium dioxide (TIO_2) in the Earth's crust are rutile, anatase, and brookite. The first natural occurrence of an unnamed, dense polymorph of TiO_2, attributed to shock metamorphism, was found in the shocked gneisses of the Ries impact crater in Germany (Goresy et al. 2001). Similar shocked rutile has been identified in breccias from the Eocene Chesapeake Bay impact structure in the USA (Jackson et al. 2006). Recently from the ONGC drill core samples of the Proterozoic granite, we have identified in SEM study a shock-induced ultradense polymorph of rutile in the granitic basement rock, which is similar to that of the Ries crater and the Chesapeake Bay impact structure (Fig. 8.24D, E). Experimental data suggests that shocked rutiles are formed at high pressure between 16 and 20 gigapascals, generated by a large body impact. Both pseudotachylite and shocked rutile in the basement rock suggest that the Mesoproterozoic granite was the primary target rock for the Shiva bolide impact.

The Shiva bolide ($\sim$40 km diameter) generated lethal amounts of kinetic energy of 1.45 x 10^{25} joules. The impact was so powerful that it caused several geodynamic anomalies: it fragmented, sheared, and deformed the lithosphere across the western Indian margin and contributed to major plate reorganization in the Indian Ocean. Geophysical study suggests that the Shiva impact sheared, thinned, and deformed the lithosphere near the Mumbai coast, where the crust-mantle boundary was lifted up more than 50 km, showing unusually high heat flow (Pandey and Agarwal 2001). It initiated rifting between India and Seychelles in the west, creating the Arabian Sea (Chatterjee et al. 2006, Chatterjee et al. 2017).

Killing Mechanism

There is now a general consensus that two asteroids hit the Earth at the end of the Cretaceous, and the twin impacts were a primary cause for the final demise of the dinosaurs, as well as other organisms on land and in the sea (Lerbekmo 2014). The evidence for two large bolide impacts on Earth at the end of the Cretaceous has come from opposite sides of the globe, one on the Yucatan Peninsula of Mexico creating the Chicxulub crater (Hildebrand et al. 1995) and the other on the western shelf of India excavating the Shiva crater (Chatterjee et al. 2006). Another small crater ($\sim$24 km diameter), Boltysh crater at Ukraine, also formed at the K-Pg boundary; the cosmic signatures of three successive impact events at the K-Pg boundary been recorded in Gujarat, India.

The Anjar volcano-sedimentary section in Gujarat consists nine lava flows (F1–F9) four intertrappean beds (Bhandari et al. 1996). The third intertrappean bed, about 6 m thick, contains three closely-spaced iridium and fullerene anomalies at the K-Pg boundary, supporting multiple impact events (Parthasarathy et al. 2002). These three iridium layers are designated as Br-1, Br-2, and Br-2, from top to bottom; they appear to be primary ejecta layers deposited in quick succession from different vaporized meteorite sources from different sites.

We suggested that Br-1 signals the Shiva impact event, Br-2 the Boltysh, and Br-3 may correspond with the Chicxulub impact event. If so, the Anjar section may hold crucial evidence for three distinct episodes of global impact events during the K-Pg transition: Chicxulub in Mexico, Shiva in India, and Boltysh in Ukraine (Chatterjee et al. 2006). Similarly, at the K-Pg section in Oman, there are two distinct iridium anomalies, separated by more than 1 m-thick sediments, which supports the twin impact scenario (Ellwood et al. 2003). The Chicxulub-Shiva one-two impact killer punch, combined with the Deccan volcanism, caused rapid and profound global climate perturbations. Large bolide impacts are disastrous for the biosphere precisely because they exert stupendous energy bursts in extremely short time periods.

The abruptness of the dinosaur extinction suggests a key role for the bolide impacts (Brusatte et al. 2014). The twin impacts would have instantly produced devastating shock waves, a searing global heat pulse, catastrophic environmental effects such as extended darkness, nuclear winter, and acid rain. Impacts would trigger earthquakes of magnitude 13–15 on the Richter scale, generating gigantic mega-tsunami waves that propagated in all directions from

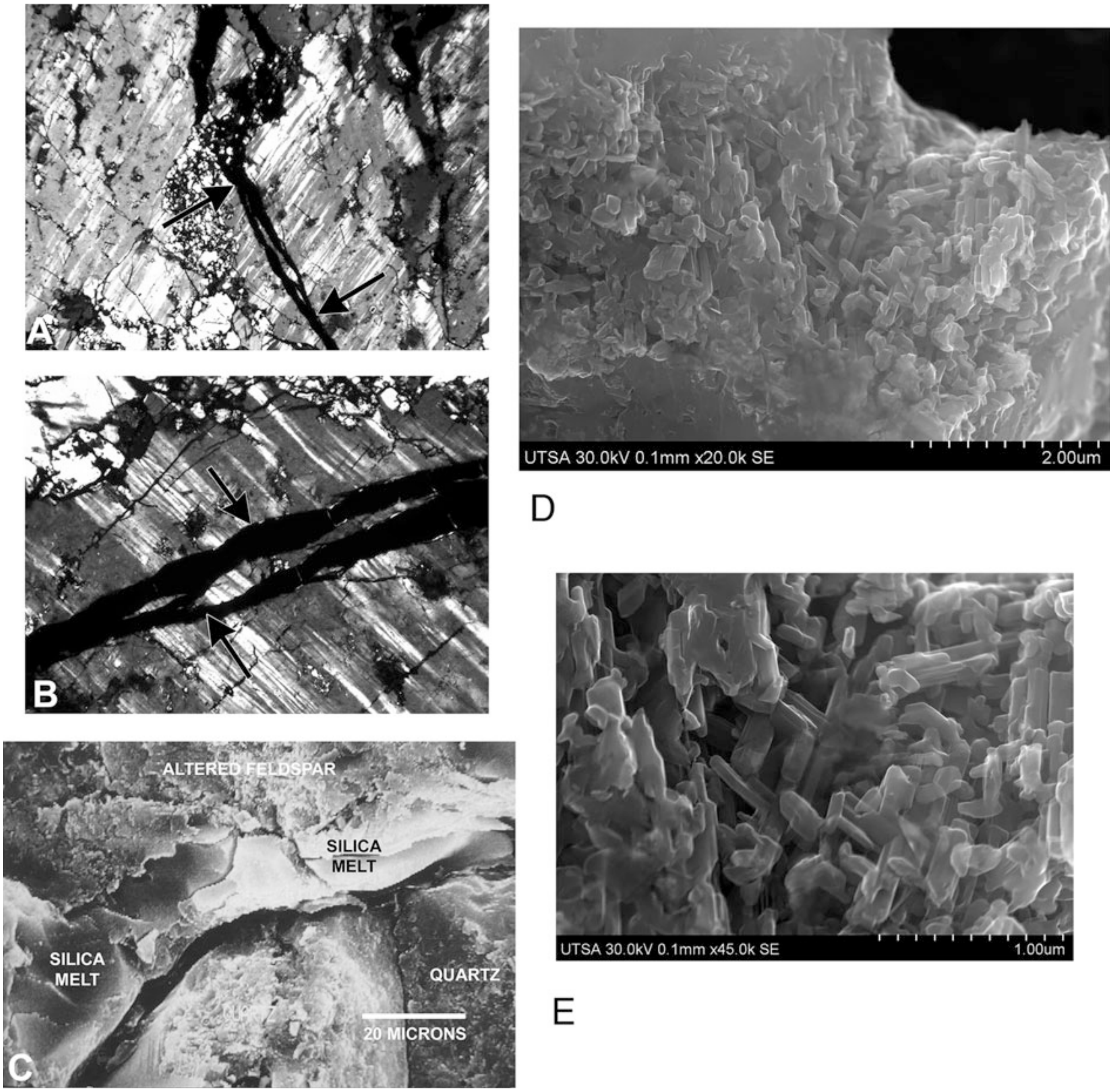


Fig. 8.24 Evidence of shock metamorphism at the basement rock of Mesoproterozoic granite, the target rock of the Shiva impact. A-B, thin section micrographs of basement granite (crossed nicols), showing the vein of pseudotachylite cutting across K-feldspar grain. The granite hosting the pseudotachylite is strongly shock-metamorphosed by the impact; C, SEM photograph of the basement granite showing the highly magnified view of the pseudotachylite vein containing pure silica melt. The impact was so powerful (>100 GPa) that it obliterated the planar deformation features (PDFs) of shocked quartz grain and turned into a melt component; D-E, SEM photographs of the basement granite showing the highly magnified view of shocked rutile (courtesy Necip Guven)

the point of impact and would flood coastal areas. The impacts would have generated more than a 100-million megaton blast (about 10,000 times that of the entire world's nuclear arsenal) and lofted vast amounts of ejecta into the atmosphere that would envelop Earth, block the Sun, and halt photosynthesis (Alvarez 1997). Millions of organisms would die instantly from the direct effect of the impact—shock heating of the atmosphere by the expanding fireball. Most of the world's vegetation would be caught in fireball (Kring and Dudra 2003). The fires consumed Earth's forests, wiped out critical terrestrial habitats and wreaked the base of the food chains. An infrared thermal pulse from a global rain of hot spherules from the K-Pg impacts could be the prime killing agents (Robertson et al. 2004). According to this model, for several hours following the impacts, the entire Earth was scorched with infrared radiation from reentering ejecta that would have killed unsheltered large animals directly and ignited global fires that consumed Earth's forests and their inhabitants. Any animal larger than 25kg was annihilated, very possibly due to insufficiency of oxygen.

Smaller species such as mammals and squamates that lived underground, or freshwater animals such as turtles and crocodiles would have been least vulnerable to heat and fire. Soot and impact ejecta chocked the sky and blocked the Sun, creating a perpetual night that halted photosynthesis and triggered a near-freezing global climate so that plants and phytoplanktons died and food chains collapsed, devastating the biosphere. Since the twin impacts occurred at the coastal region, huge tsunamis produced by the impact destroyed the costal habitat (Chatterjee et al. 2006).

Deccan Volcanism

Although twin impacts played a critical role in the K-Pg mass extinction, global climatic instability, high environmental stress, and acidification of the ocean preceded the K-Pg boundary by $\sim$1 million years (Keller 2014). The cause of the precursory climatic perturbation, that pushed some ecosystems to the tipping point, is generally attributed to the early pulses of Deccan volcanism. Deccan volcanism has long been proposed as having a causal relationship in the death of the dinosaurs at the end of the Cretaceous, but the link remains controversial. The Deccan volcanic province extends across approximately one sixth of the subcontinent, encompassing up to 1,000,000 km^2 of eruptive lavas that reach a total thickness of $\sim$3000 m near the eruptive center in western India. The main phase of Deccan eruptions initiated $\sim$250,000 years before the Cretaceous-Paleogene boundary (Schoene et al. 2015). Habitat destruction of such an extensive area, by prolonged Deccan volcanism, pushed Maastrichtian dinosaurs to the outer fringe of the volcanic province, causing population declines in many dinosaur species (Fig. 8.25). However, it is clear that the major dinosaur species persisted in India during the second Deccan phase, up until the K-Pg boundary iridium layer in the Anjar section, suggesting that at least in India, Deccan volcanism did not cause any substantial change in dinosaur species richness.

However, Deccan volcanism might have a direct adverse effect on marine organisms. The Deccan Traps have released tens of thousands of petagrams of carbon dioxide and methane, leading to tropical warming and loss of oxygen from the ocean's interior. Temperature-dependent anoxia may explain severity of end-Cretaceous marine mass extinction. Volcanically induced warming is clearly a powerful driver of marine anoxia.

Volcanic emissions led to increasingly toxic environment by releasing mercury into the atmosphere in gaseous form that contaminated water and soil. Mercury emitted into the air eventually settles globally into oceans, rivers and lakes, and is subsequently deposited in sediments. The toxic effects of mercury pollution are deleterious for wildlife and the entire ecosystem. Font et al. (2016) reported a high concentration of mercury (Hg) anomaly (>2 orders of magnitude) at the K-Pg transition in marine sections of France, Italy, Brazil, Argentina, which is linked to the major Deccan eruption episode. There were numerous, pulsed elevations of mercury concentrations in the marine sediments globally during the K-Pg transition. These peaks show that mass extinction coincided with large-scale, episodic volcanism. Pulsing mercury emissions from Deccan volcanism occurring over a million years, might have poisoned the ocean-atmosphere system during the end-Cretaceous crisis. High mercury concentrations polluting an environment reduce the reproductive success and impose hatchling failure of many birds and turtles. In recent times, bird hatchlings are especially at risk from toxic chemicals such as mercury, which accumulates in the eggs in increasing concentration; this may adversely influence embryonic development, or the critical period of hatching, or the first days of the hatched chick's life (Becker et al. 1993). Thousands of dinosaur eggs have been discovered, stretching 1000 km along the Lameta Formation of India, but they seem to be empty; all but one isolated example lack embryos. Did Deccan volcanisms trigger the hatchling failure of dinosaurs in India by mercury-induced poisoning? We don't know but this raises an interesting possibility. Perhaps detection of mercury levels in the titanosaur eggshell may answer this question.

The episodic nature of Deccan volcanism may possibly explain the survival of many freshwater and terrestrial communities in the Deccan volcanic province during the periods of quiescence. Deccan Traps might have contributed to the latest Cretaceous environmental change and biological turnover in the marine realm for a prolonged period, before and after the twin impacts. Enormous amounts of CO_2, SO_2 and other pollutants from the Deccan eruptions possibly caused climate warming and cooling, ocean acidification, and high-stress-environments. The pattern of extinctions seems unequivocal in the rapid demise of planktic foraminifera that is related to the main phase of Deccan eruption. The strong carbonate dissolution effects are observed in foraminifera from the intertrappean and infratrappean sediments of the Krishna-Godavari wells, as well as in the Meghalaya section. This indicates ocean acidification due to volcanic CO_2 and SO_2 resulting in decreased pH of ocean waters (Keller 2014). The Deccan eruption coincided with long-term global warming of 4 °C in the oceans and 8 °C on land, followed by rapid short-term "impact winter" conditions induced by twin impacts (Scotese 2015, Vellekoop et al. 2016).

The environmental crisis induced by the Deccan volcanic emissions would have been intensified a million times by the collision of twin asteroids at the K-Pg boundary. The killing mechanism of marine biota was likely ocean acidification, and mercury poisoning induced by volcanism, resulting in

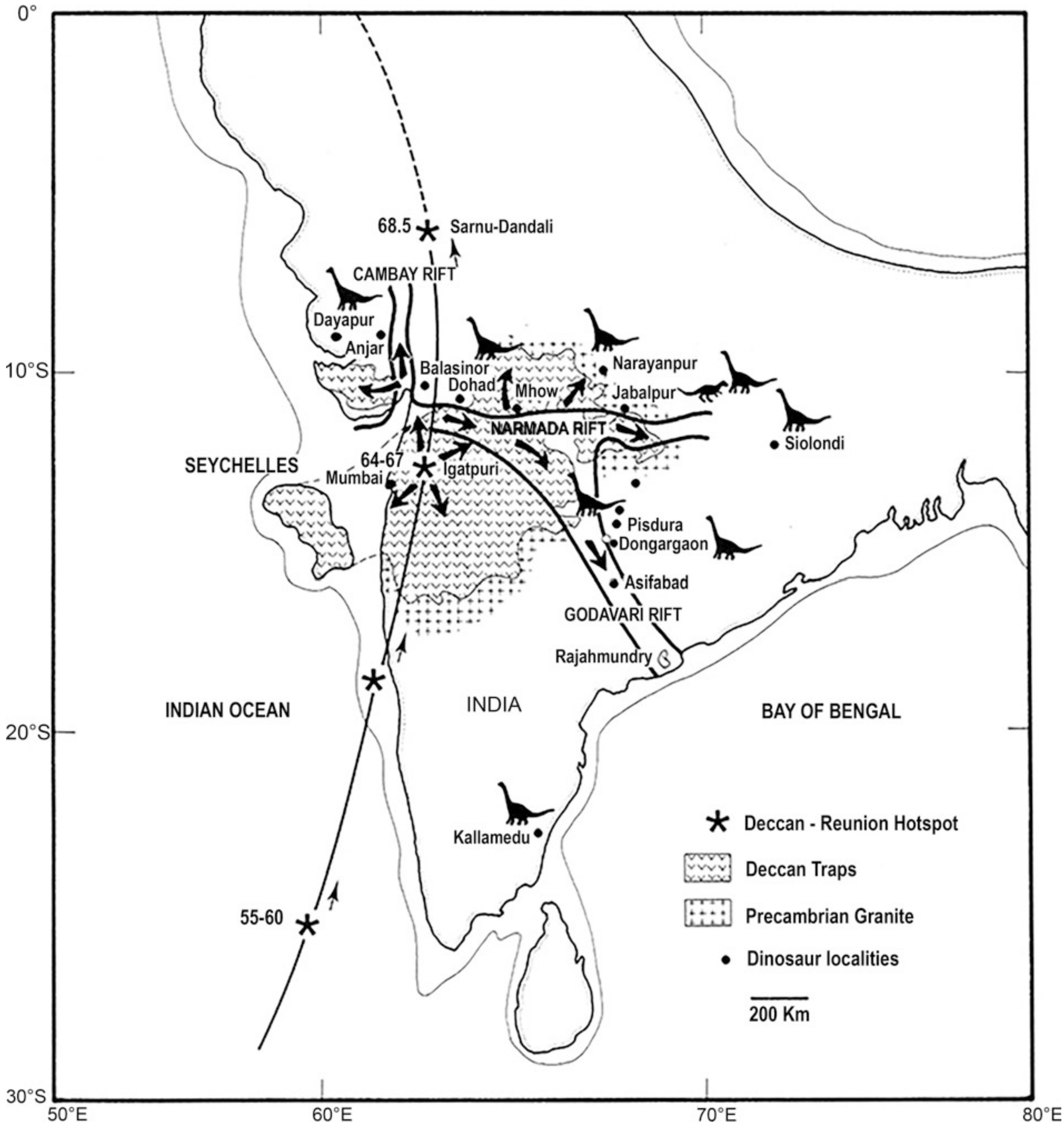


Fig. 8.25 Sketch map showing localities of Maastrichtian dinosaurs around the Deccan volcanic province. The position of India was reconstructed during the Late Cretaceous time ($\sim$65 Ma); asterisks indicate the Deccan-Reunion hotspot track; the plume might have started from the Parh Group of volcanics of northeastern Baluchistan, the northernmost manifestation of the Deccan volcanism (shown by dashed line). Dinosaurs were thriving and reproducing along the periphery of the Deccan volcanic province, when the lava was erupting (modified from Chatterjee and Rudra 1996)

the carbonate crisis that led to the collapse of the marine food chain associated with extreme climatic perturbation and anoxic condition. The Deccan volcanic model can better explain the selectivity and the stair-step extinction pattern in marine organisms. Deccan volcanism was an accomplice, but not the main killer, in the massive destruction of life, especially the dinosaurs and other terrestrial organisms. It seems that twin impacts were the proximate cause of the K-Pg extinction, whereas the long-term volcanism contributed heavily to the breakdown of stable ecological communities, and disrupted the biosphere. The K-Pg extinction was a compound crisis, induced by both impact and volcanism. It seems that twin impacts at the K-Pg boundary were the final blow to the already overstressed global

ecosystems initiated by the prolonged period of Deccan volcanism (Chatterjee 2015). Two large impacts such as Shiva and Chicxulub in quick succession on the antipodal position, in concert with Deccan eruptions, would have devastating effects globally leading to climatic and environmental catastrophes that wiped out dinosaurs and many organisms at the K-Pg boundary.

Impact-Induced Volcanism

The Deccan volcanism began spewing more lava coincident to the Shiva bolide impact, on the western shelf of India. This was possibly precipitated by the closely proximity of the Shiva impact to the Deccan-Reunion Hotspot, 66 million years ago. A cause-and-effect connection between the bolide impact and Deccan volcanism has been the subject of extensive discussion and speculation. The main phase of Deccan volcanism, which accounts for about 80% of the 3,500-m-thick pile, is reported to have erupted within a short time in C29R, within a 50,000-year period (Schoene et al. 2015). This rapid phase 2 of Deccan eruptions also appeared to coincide with the date for the Shiva impact. At the K-Pg boundary, the normal trickle of Deccan lava eruption became a torrent, as evinced by the thick pile of phase 2 Deccan volcanism. The Shiva impact was so powerful that it not only threw huge clouds of dust into atmosphere, but also rattled the magma chamber of the Earth, causing spectacular Deccan volcanic eruptions. The spatial and temporal coincidence of Deccan volcanism with the Shiva crater led to the suggestion that the main phase of the Deccan Trap might have been triggered by the Shiva impact (Chatterjee and Rudra 1996). Impact could enhance the volcanic activity through decompression melting beneath or near the impact site (Jones et al. 2002). In close geographic proximity of the Shiva crater, the head of the Reunion plume during the K-Pg boundary was positioned near Igatpuri, creating the spectacular Deccan eruption (Fig. 8.23B).

The Deccan volcanic province is one of the largest volcanic eruptions in earth's history, comprising >1.3 million km^3 of erupted lava flows throughout west-central India. Alkali igneous complexes within the Deccan lavas, interpreted as the fluid impact ejecta, straddle the traces of the asteroid impact; this is indicated by a spike in iridium levels. This strengthens the idea that the Shiva impact and the Deccan eruptions happened coincident in geographic proximity and very close together in time (Chatterjee et al. 2006). Perhaps, these two catastrophic events in India were genetically related, i.e., the Shiva impact enhanced the Deccan phase 2 eruption by expansion of the deep-crustal magma chamber, triggering the rapid eruption during the K-Pg boundary (Chatterjee et al. 2017). The spurt in Deccan volcanism at the K-Pg boundary was possibly enhanced by the Shiva impact.

Aftermath of the K-Pg Extinction

Puzzling mass extinctions punctuate the Earth's history. Mass extinction events may be the primary force for major shifts in life's history and important drivers of evolutionary novelty. When a mass extinction strikes, it is not necessarily the most fit fauna that survive, but merely the most fortunate. After each mass extinction event, life rebounds, is revamped, and diversifies. Many dominant groups in the pre-extinction period are eliminated, providing opportunities for surviving lineages to proliferate. Mass extinctions are fundamental game-changers in the history of life, by removing successful incumbents, and by encouraging the meek to proliferate and inherit the Earth.

The K-Pg extinction is a chilling reminder of the fragility of earth's biosphere. Life was devastated but biota that survived the bottleneck effect, inhabited a world in which the slate was wiped clean, and vast and diverse ecological zones were newly available for new-comers for exploration and exploitation. Following the combined cataclysm, evolution in all groups of vertebrates, especially modern birds and placental mammals, was explosive and diverse. The aftermath of twin impacts eliminated dinosaurs from land, and opened up opportunities for placental mammals and primates to evolve and flourish. The K-Pg extinction left an impoverished fauna on the land with the disappearance of nonavian dinosaurs and shallow marine organisms, but a rebound during the early Paleogene once again brought back biodiversity. The demise of the dinosaurs left vast regions virtually devoid of large land animals; these vacant niches were soon occupied with newly evolving and diversifying mammals. It led to the explosive evolution of placentals including primates, our early ancestors.

Mammals evolved into diverse ecophenotypes during the Jurassic and Cretaceous, but compared to extant species were generally small. All mammal groups were severely affected by the end-Cretaceous extinction, particularly metatherians. The survivors proliferated rapidly after the dinosaur extinction, forming diverse mammalian faunas in North America in Early Paleocene. It is tempting to consider that the death of dinosaurs at the end of the Cretaceous lifted a major impediment to the ecological expansion of placental mammals. That view might be true, but the tempo and mode of ecological replacement of dinosaurs by placental mammals was not instantaneous in the Paleocene, but was more gradual. It occurred over several stages, across the 10 million years following the extinction event, eventually culminating in the emergence of the Eocene, when the traumatized ecosystems had finally recovered. The post-K-Pg boundary high stress conditions and delayed recovery can be attributed to last phase 3 of Deccan volcanism during Early Danian. A gradual recovery to larger morphotypes and higher

diversity of placentals began only after the Deccan phase 3 ended, and full recovery was restored during the Paleocene-Eocene Thermal Maximum (PETM), when India collided with Asia. At that time, placental mammals underwent an explosive evolution, as recorded in the rich fossils record of the Cambay Shale Formation of Vastan, Gujarat. With the demise of the dinosaurs, mammals evolved a greater variety of forms in the newly vacated niches. We see this in the rapid increase of their body size, and the ecological diversity of placental mammals that are today found in the Cambay Shale Formation. India became the major center for several groups of placental radiation such as bats, whales, artiodactyls, perissodactyls, primates, and lagomorphs, thus strengthening the 'out-of-India' hypothesis (Chatterjee et al. 2017).

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